School of Electronic Engineering
and Computer Science

Technological Support for Highland Piping Tuition and Practice

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Media and Arts Technology PhD Programme

PhD Thesis

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Abstract

This thesis presents a complete hardware and software system to support the learning process associated with the Great Highland Bagpipe (GHB). A digital bagpipe chanter interface has been developed to enable accurate measurement of the player's finger movements and bag pressure technique, allowing detailed performance data to be captured and analysed using the software components of the system.

To address the challenge of learning the diverse array of ornamentation techniques that are a central aspect of Highland piping, a novel algorithm is presented for the recognition and evaluation of a wide range of embellishments performed using the digital chanter. This allows feedback on the player's execution of the ornaments to be generated. The ornament detection facility is also shown to be effective for automatic transcription of bagpipe notation, and for performance scoring against a ground truth recording in a game interface, *Bagpipe Hero*.

A graphical user interface (GUI) program provides facilities for visualisation, playback and comparison of multiple performances, and for automatic detection and description of piping-specific fingering and ornamentation errors. The development of the GUI was informed by feedback from expert pipers and a small-scale user study with students. The complete system was tested in a series of studies examining both lesson and solo practice situations. A detailed analysis of these sessions was conducted, and a range of usage patterns was observed in terms of how the system contributed to the different learning environments.

This work is an example of a digital interface designed to connect to a long established and highly formalised musical style. Through careful consideration of the specific challenges faced in teaching and learning the bagpipes, this thesis demonstrates how digital technologies can provide a meaningful contribution to even the most conservative cultural traditions.

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Chapter 1

Introduction

1.1 Motivation and Aims

The musical culture of the Great Highland Bagpipe (GHB) is in many ways quite distinct from other styles of Western folk and classical music. Widely considered to be the national instrument of Scotland (Dickson, 2009), the GHB has long maintained a deep military connection, and the discipline and uniformity associated with all aspects of the armed forces are strongly reflected in the Highland piping tradition. In particular, ornamentation is a central aspect of GHB music, and over the centuries an extensive array of formally defined embellishment techniques has become established. Even reasonably simple bagpipe tunes require the performer to know a wide variety of distinct ornaments, and to execute them with meticulous precision. This stylistic rigidity, coupled with the level of physical endurance required to produce a consistent sound, can cause the learning curve associated with the GHB to be intimidatingly steep to the beginner.

In broad terms, the aim of this PhD research is to investigate the use of digital technologies to support the GHB learning process. This thesis presents a custom-designed electronic bagpipe hardware interface and accompanying software system, developed to address the specific requirements of the piping community. Section 1.2 provides some background on the GHB itself and the specific challenges it poses for aspiring pipers. An outline of the remainder of this thesis, detailing the various tools developed during the project to address these concerns, is presented in Section 1.3.

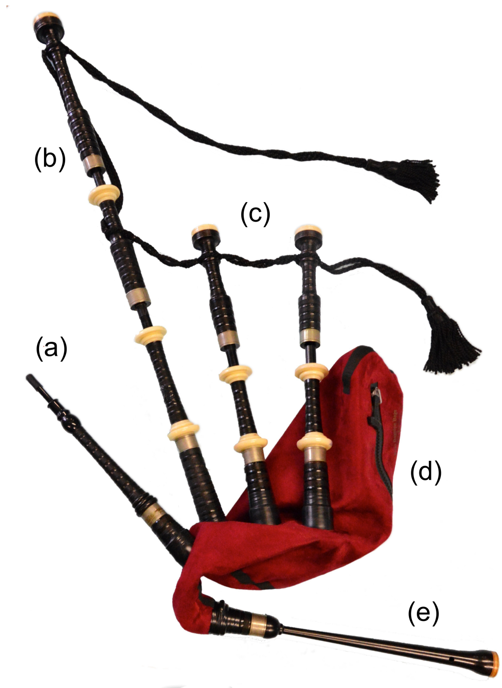


Figure 1.1: Great Highland Bagpipe showing (a) blowpipe, (b) bass drone, (c) tenor drones, (d) bag, and (e) chanter.

1.2 The Great Highland Bagpipe (GHB)

The GHB (Figure 1.1) is comprised of five individual pipes (two tenor drones, one bass drone, the blowpipe and the melody pipe or chanter) attached to an airtight bag which acts as an air reservoir. The bag is held under the player's arm, with the drones resting over the shoulder. By maintaining a constant pressure on the bag with the elbow, the player ensures a steady flow of air through the reeds in the drones and chanter.

It is worth noting that the level of air flow and pressure on the bag are generally not used as expressive parameters, but rather kept as consistent as possible in order to produce a continuous, unbroken sound (Dannenberg, Brown, Zeglin, & Lupish, 2005). The bass and tenor drones produce a uniform octave accompaniment which remains unchanged regardless of the melody. Therefore, at least in traditional piping, the chanter is the sole means of expressive control of the GHB.

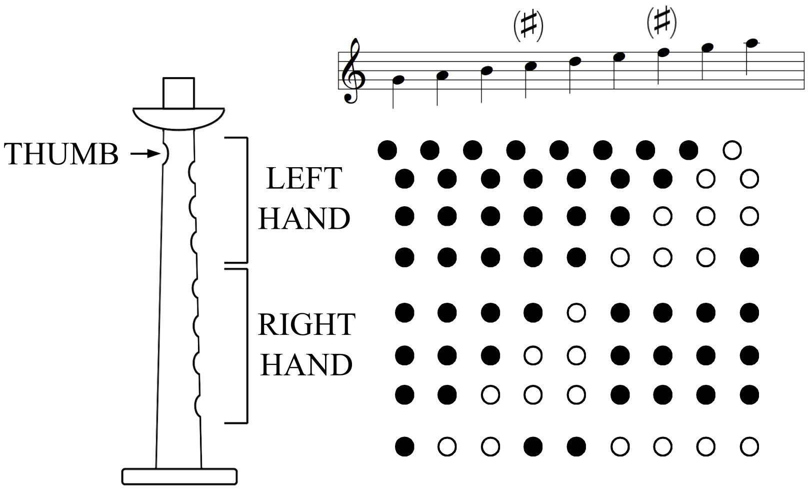


Figure 1.2: Highland bagpipe scale and fingerings.

1.2.1 The Chanter

1.2.1.1 Scale and Fingering

The chanter is held in both hands, and is played by covering and uncovering the eight tone holes. GHB chanters have a conical bore, and use a double reed similar to an oboe or bassoon. Since the reed cannot be "overblown" into a second octave (as can the Irish uilleann pipes for example), the traditional Highland piping scale is limited to nine notes. The scale and its associated fingerings are illustrated in Figure 1.2. This diagram raises two important details. Firstly, the Highland bagpipe is a transposing instrument, sounding approximately a semitone above the notated pitch (Dickson, 2009). Throughout this thesis, notes will be referred to by their piping names as opposed to concert pitch.

Furthermore, although no key signature is given (as is typical of all GHB music), the C and F of the scale are in fact C♯ and F♯. The chanter can therefore reproduce a full *Mixolydian* scale, with an additional 7th (Low G) below the tonic (A). Additional "cross fingerings" for C♮ and F♮ have been developed in recent years, and are common among many contemporary pipers. However, these have not been widely accepted into traditional piping circles, and hence the standard (sharp) fingerings shown in Figure 1.2 are invariably referred to simply as "C" and "F".

Figure 1.3: A traditional practice chanter.

1.2.1.2 The Practice Chanter

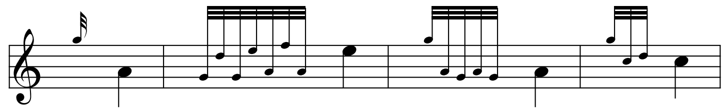
The practice chanter (Figure 1.3) is a single pipe instrument with no bag, which uses the same fingering patterns as the GHB chanter. Sounding approximately an octave below the GHB, and with considerably lower volume, practice chanters are used extensively by many pipers to learn new tunes and refine fingering technique. However, this does not allow the user to practice keeping a steady pressure on the bag, nor to maintain the necessary levels of physical endurance required to play the GHB, and thus regular sessions with a full set of pipes are still essential.

1.2.2 Ornamentation

In addition to its restricted melodic range, the GHB provides no facility for dynamic control, and hence has only one (not inconsiderable) volume level. Moreover, the fact that both drones and chanter produce a constant, uninterrupted sound prevents the use of silences or timbral variations for the purposes of emphasis and articulation. To address these limitations, pipers employ a variety of ornaments or embellishments[1] to separate and accentuate the melody notes. These take the form of one or more short gracenotes, performed in a specific order. A wide range of ornaments exist (Appendix A), from individual gracenotes to more elaborate embellishments such as the *birl* and *crunluath* (Figure 1.4). These are rigorously and formally defined, and their correct execution is an integral aspect of piping technique (Shepherd, R.T., 2002).

The aspiring piper must therefore invest considerable effort to learn and master

[1]The terms "ornament" and "embellishment" are used interchangeably throughout this thesis.



(a) (b) (c) (d)

Figure 1.4: Examples of Highland bagpipe ornamentation: (a) G gracenote, (b) *crunluath*, (c) *birl*, (d) *doubling on C*.

at least the basic ornaments before attempting all but the simplest tunes. This process can often take six to twelve months of regular and disciplined practice, and is particularly challenging in situations where lessons with a tutor are infrequent. Moreover, to the untrained ear, it can be somewhat difficult to discern whether or not an ornament was executed correctly. In the absence of an experienced instructor to provide immediate criticism in such instances, the novice player's inability to evaluate their own technique accurately can lead to wasted practice time and the introduction of bad habits.

1.2.3 Rhythmic Phrasing

Together with ornamentation, variations in rhythmic phrasing are a central element of expressive bagpipe performance, and one of the primary means by which proficient solo pipers can convey their own interpretations of the otherwise largely inflexible traditional repertoire. In particular, while there are some general guidelines as to where certain embellishments should be performed with regard to the beat, this is often a matter of personal preference on the part of the player. Additionally, precise timing is essential in the context of pipe band performance; it is the highest form of praise for such ensembles to be described as sounding "like a single set of pipes".

Piping instructors will therefore seek to guide their students towards particular phrasing characteristics depending on the desired expressive effect. However, teaching a student about the subtleties of these rhythmic features can be a challenging task. While singing or playing a passage for the pupil to repeat is undoubtedly effective, it is often necessary for the tutor to describe their intentions verbally. This can lead to the use of somewhat abstract language such as *"push out these notes"* and *"the G gracenote takes you to the E doubling on the beat"*, which can be difficult to understand, even for students with significant experience of other musical instruments.

1.2.4 GHB Fingering Errors

1.2.4.1 False Fingering

False fingering refers to the practice of playing a note (the pitch of which is determined primarily by the highest open hole) without executing the corresponding fingering on the lower holes of the chanter. While this is seen as serious technical flaw in traditional piping circles, the comparatively subtle differences in sound between correct and incorrect fingerings are not always easy to discern. Moreover, even when a clear change in pitch or timbre is perceptible, the problem can often be wrongly attributed to a difference source, such as unsteady bag pressure. False fingering is therefore a difficult habit to diagnose and correct, particularly for inexperienced players practicing alone.

1.2.4.2 Crossing Noises

When changing between two different notes on the chanter, the player will often be required to move more than one finger simultaneously. If this is not executed with sufficient care, such transitions can lead to the inclusion of short unwanted pitches (for example, a momentary Low G caused by failure to uncover the bottom hole in a timely manner when moving from D to E). These are referred to as *crossing noises*, and are considered within the GHB community to represent extremely poor technique.

1.3 Outline of Thesis

This section provides an outline of the structure of this thesis, and summarises the developments and outcomes presented in each chapter.

Chapter 2 provides a review of existing research which forms the background for this work. In Section 2.1, sensing strategies for digital musical instruments are discussed, and the issues associated with developing technologies for traditional musical cultures considered. Section 2.2 concerns the use of technology to support musical instrument pedagogy, particularly systems designed to assist in one-to-one tuition and solo practice environments. The chapter concludes with a summary of the key points, and identifies how they can applied to the GHB learning process.

Chapter 3 describes the development of a digital bagpipe chanter interface, which forms the hardware component of the complete Highland piping tuition and practice system. Two iterations of the design are discussed, and a detailed description of the sensing strategies, physical construction and sound generation approach is presented.

Chapter 4 concerns the development of an algorithm for the automatic recognition and evaluation of Highland piping ornamentation in performances recorded using the digital chanter interface. Two variants are described and evaluated, and the final approach is shown to provide accurate results even in cases where the performed embellishments are poorly executed (e.g. by student pipers). Lastly, the potential of the algorithm to enable automatic transcription of bagpipe music is demonstrated.

Chapter 5 describes the development of a graphical user interface (GUI) application to assist in Highland piping tuition and solo practice. The program uses sensor input from the digital chanter (Chapter 3), and incorporates the ornament recognition algorithm developed in Chapter 4, bringing these threads of work together to form a complete hardware and software system to support the GHB learning process.

The final design is informed by feedback gathered during a pilot study (described in Section 5.3), and includes controls for recording, playback and visualisation of performances with the aim of assisting an instructor in describing their feedback on a student's playing. Additional developments for automatic identification of errors in ornamentation and fingering during solo practice are discussed, and a game interface (*Bagpipe Hero*) is presented, which aims to increase motivation among younger learners.

Chapter 6 seeks to assess the effectiveness of the complete digital chanter system in supporting GHB learning through a series of individual studies. An extended user study was conducted in a boarding school with an experienced piping instructor and 17 students over a period of 5 weeks, in order to determine how such a tool might be integrated into the traditional lesson environment. A smaller-scale study was carried out with 4 adult pipers to investigate how the system was used as part of their own solo practice. Lastly, a listening test to evaluate the perceptual relevance of the *Bagpipe Hero* scoring algorithm is described, the results of which indicate a significant level of alignment between the output of the system and numerical scores assigned to the same performances by experienced human bagpipers.

Chapter 7 concludes by summarising the contributions of this thesis, identifying areas for future research, and reflecting on the processes and outcomes of the work, both in terms of the specific field of Highland piping and how they might relate to other musical traditions.

Chapter 2

Literature Review

This chapter provides a review of existing work which constitutes the background for this PhD research. Section 2.1 concerns the field of digital musical instruments (DMIs). After a brief overview of the general considerations involved in DMI design, Section 2.1.1 describes existing digital bagpipe technologies, and identifies their limitations as practice tools to support the GHB learning process. Section 2.1.2 investigates various sensing strategies used to detect performers' interactions with their instruments. In Section 2.1.3, the issues associated with developing technologies for specific musical traditions are discussed. Evaluation strategies to assess the effectiveness of DMIs are considered in Section 2.1.4.

Having covered the literature surrounding the hardware aspect of this work, Section 2.2 examines the use of technology to support musical instrument pedagogy. The instructional strategies and psychological theories of learning involved in computer-assisted musical education systems are outlined in Section 2.2.1. Specific research projects addressing technological assistance for solo instrumental practice, tuition and remote learning are discussed in Sections 2.2.2, 2.2.3 and 2.2.4 respectively. Section 2.3 provides a summary of the key points addressed in this chapter, and identifies how they can applied to the GHB.

2.1 Digital Musical Instruments and Interfaces

The design and development of digital musical instruments (DMIs) and other technological interfaces for musical expression is an active field of research. A comprehensive review of existing work in this domain can be found in (Miranda &

Wanderley, 2006). This section provides a brief overview of the general concepts associated with DMI design before moving into the specific area of electronic bagpipes in Section 2.1.1.

The spectrum of DMIs extends from entirely novel devices bearing little or no resemblance to traditional musical paradigms, to acoustic instruments which have been *augmented* through the addition of electronic components to provide new expressive possibilities (Jordà, 2004). In either case, the interaction between performer and instrument is facilitated through the use of sensors to detect the various physical gestures (e.g. finger movements on a keyboard, air flow in a flute) on the part of the player. A range of such technologies exist, and their applications in real-time sound synthesis and control of DMIs have been explored in depth (Wanderley & Depalle, 2004; Medeiros & Wanderley, 2014).

A key distinction between different sensing strategies is the concept of *discrete* versus *continuous* output. Discrete sensors (such as buttons and switches) provide a finite number of outputs; in the case of a two-way switch, the output is either on or off. Continuous sensors (e.g. potentiometers) are those which provide a full analogue range of outputs between a maximum and minimum value. Among the most fundamental considerations in DMI design are which type of sensor would be best suited to the application in question, and how the resulting sensor readings should be *mapped* to the various parameters (e.g. pitch, volume, and timbre) of the sonic output.

The importance of careful consideration with regard to parameter mappings is discussed in (Hunt, Wanderley, & Paradis, 2003). The article asserts that the mapping between the input parameters and the resulting sound can "define the very essence of an instrument". Several experiments are presented in which participants played DMIs consisting of exactly the same physical interface and sound production source, the only difference being the mapping between input and output parameters. The choice of mappings was shown to have a profound effect on the users' experiences with the instruments in terms of ease of control, perceived expressivity and level of engagement.

In (Hunt & Wanderley, 2002), mappings between one set of parameters and another are categorised as either *one-to-one* (one input parameter controls one output parameter), *one-to-many* (one input parameter can influence several output parameters), or *many-to-one* (one output parameter is influenced by several input parameters). The article describes how combinations of these three strategies can be built up to form multi-layer mapping models (e.g. several sensor values are mapped to one “energy” parameter; “energy” is mapped to a more abstract “brightness” parameter; and “brightness” maps to multiple synthesis parameters to produce the sound) which the authors suggest can simplify the design process by allowing the designer to focus on the desired sonic result.

An extensive discussion of gesture sensing and mapping strategies is provided in (Benford, 2010), which categorises gestural input in terms of *expected*, *sensed* and *desired* actions. The majority of DMI design tends to focus on actions which fit all of these descriptors. This is unsurprising, as it corresponds to the intuitive process of detecting natural performer movements which lie within the scope of the chosen sensor(s), and mapping these to an appropriate output. However, the article suggests that other classes of action should also be considered. For example, in the case that some expected movements cannot be detected by the sensors, this implies that the instrument is not sufficiently responsive, and that the designer should either extend the capabilities of the sensors or restrict the performer’s physical gestures to within a suitable range.

There may also be certain expected actions for which there is no desired output, such as picking up or laying down an instrument. Where such gestures can be sensed, they should be deliberately ignored in the output mapping to avoid unwanted sounds being produced. Less intuitive, but equally informative is the situation where unexpected movements can be sensed and mapped to a desired output. Such gestures not only allow innovative performers to explore the sonic possibilities of the DMI through novel and experimental techniques, but can also be particularly useful for *meta-level* control of the instrument (e.g. adjusting tonal parameters, and similar operations which are often accomplished using foot-switches).

The following section discusses sensing strategies as applied to the particular field of digital bagpipe chanters, as well as other technological developments that directly relate to the Highland piping community. A more general review citing specific examples of physical gesture sensing approaches in traditional musical instrument performance is provided in Section 2.1.2.

2.1.1 Existing Digital Bagpipe Technologies

In recent years, a number of bagpipe-related research projects have emerged, from the construction of custom electronic chanter interfaces capable of driving a remote-controlled car (Kirk & Leider, 2007), to GHB-playing robots (Dannenberg et al., 2005). This section provides an overview of existing digital bagpipe technologies, and discusses their limitations as tools to support traditional Highland piping practice.

Several brands of electronic GHB chanter have been developed commercially, of which the DegerPipes[1], TechnoPipes[2] and Redpipes[3] are most prominent. These use single capacitive touch-switches in place of the tone holes, and generate audio output using wavetable synthesis. While such devices have found moderate acceptance among some modern folk-fusion groups for live concerts, the sound produced is rarely deemed sufficient for solo performance or recording purposes. This issue has been addressed by the *Studio Piper* project[4], a desktop software application which uses sampled acoustic recordings to produce convincing results.

The EpipE (Cannon, Hughes, & Ó Modhráin, 2003; Hughes, Cannon, & Ó Modhráin, 2004) is a uilleann bagpipe chanter interface, which extends the capacitive sensing approach to include an array of sixteen small binary touch-switches for each hole. The number of electrodes was chosen such that for each individual sensor, the corresponding change in frequency would be less than the Just Noticeable Difference (JND) discernible by the human ear (Zwicker, Flottorp, & Stevens, 1957), giving the impression of continuous frequency variation. The FrankenPipe (Kirk & Leider, 2007) instead uses photoresistors mounted inside the holes of an acoustic GHB chanter. This provides a wide analogue range for each hole, and has the advantage of retaining the physical feel of a traditional chanter.

One existing software product that is specifically aimed at the traditional Highland piping community is the *PiobMaster* notation program[5], which features drop-down menus for a wide range of GHB ornaments to accelerate the otherwise time-consuming process of notating bagpipe music. It does not, however, support automatic transcription from user input, as is possible with more generic notation packages.

An obvious benefit of any digital musical instrument is the potential for silent practice using headphones. However, existing electronic chanters have several limitations in terms of their effectiveness as practice tools. Firstly, the capacitive

[1] `http://www.deger.com/`
[2] `http://www.fagerstrom.com/technopipes/`
[3] `http://redpipes.eu/`
[4] `http://www.epipes.co.uk/`
[5] `http://www.ceolmor-software.com/piobmasterpro.html`

touch-switches used to detect the player's finger movements are discrete in nature (i.e. each hole is either fully covered or fully open), which does not accurately reflect the tone-holes of an acoustic chanter. While the practice of gradually covering or uncovering holes to slide between notes is not used in traditional piping, it could be argued that any digital practice interface should mirror the physical characteristics of its acoustic counterpart as closely as possible.

Moreover, and perhaps more importantly, it should be noted that commercially available digital bagpipes make no sonic distinction between correct and incorrect ("false") fingerings of a given note. Consultation with an experienced piping instructor during the early stages of this research indicated significant concern that extensive use of electronic chanters for practice purposes could therefore cause students to develop serious false fingering habits.

Lastly, playing the GHB requires a significant degree of physical exertion in order to keep the bag filled with air. Without regular practice on an acoustic bagpipe, it is difficult to maintain the necessary levels of endurance. A comprehensive digital practice tool should therefore support this vital aspect of bagpipe playing. The author is not aware of any existing electronic chanter which can be connected to a standard set of bagpipes and controlled directly using air pressure. The *Redpipes Caledonia* model is a full size electronic GHB set, which does incorporate a blowpipe for the purposes of air pressure control. However, at over £1000 this product is intended as a professional performance instrument rather than a practice tool.

2.1.2 Sensing Strategies on Traditional Musical Instruments

In many acoustic instruments, the sound produced is strongly dependent on extremely precise, small-scale control gestures on the part of the player. To allow a similar level of fine-grained control of digital musical interfaces, an accurate means of measuring such interactions is necessary. There is an abundance of research into sensing strategies to capture how performers interact with their instruments. This section provides a brief overview of some key studies in this field, starting with those most similar to the bagpipes (i.e. woodwind) before discussing other families of instruments.

Woodwind Instruments

The CyberWhistle (D. Menzies & Howard, 1998) is an augmented penny whistle which uses light dependent resistors (LDRs) to achieve continuous measurement of tone hole coverage. Two approaches to breath sensing were investigated; one using a sub-miniature electret microphone, and a second based on a micro-silicon bridge pressure sensor. The latter method, though more expensive, provides a wider range of sensor values and the advantage of direct pressure measurement.

Several studies have investigated sensing strategies for flute playing, either using augmented acoustic flutes or custom digital interfaces, a review of which can be found in (Siwiak, Kapur, & Carnegie, 2014). One of the earliest developments in this domain was the *MIDI Flute* (Pousset, 1992), developed at IRCAM in Paris. Several iterations of this instrument were designed, the first of which used optical sensors to detect which keys were pressed (Miranda & Wanderley, 2006, p. 46). Subsequent versions employed Hall effect sensors and magnets placed on the rings around the keypads for the same purpose. The latter approach was also employed in the design of the *Virtually Real Flute* (Ystad & Voinier, 2001), which aims to extend the sonic possibilities of the acoustic flute without obliging the performer to adjust their traditional playing techniques.

The Hyper-flute (Palacio-Quintin, 2003) incorporates a range of sensors (magnetic field sensors, button switches, an ultrasound transducer, pressure sensors, mercury tilt switches and a light sensor) to allow control of a variety of digital sound processing parameters during extended performance with a computer. In addition to key sensing, other research has focussed on capturing flautists' embouchure gestures, using hot wire sensors and pressure based detection techniques to measure air jet direction and velocity (da Silva, Wanderley, & Scavone, 2005).

Embouchure sensing has also been applied to the saxophone through the use of strain gauge sensors attached to synthetic reeds (Hofmann & Goebl, 2014). The same authors have also investigated saxophone fingering technique using force-sensitive resistors and accelerometers on the left-hand keys, and a webcam mounted on the bell of the instrument to track the player's finger movements (Hofmann, Goebl, Weilguni, Mayer, & Smetana, 2012; Hofmann, Goebl, Weilguni, & Smetana, 2013).

Brass Instruments

Musical gesture measurement in the context of brass instruments has also been explored. (Thibodeau & Wanderley, 2013) provides an extensive review of sensing strategies employed in the augmentation of acoustic trumpets. In addition to several experimental approaches based on accelerometers and hacked game pads, traditional trumpet finger movements have been captured by detecting valve position using optical sensors (Morrill & Cook, 1989; Jenkins, Wyatt, Trail, Tzanetakis, & Driessen, 2013), and Hall effect sensors (Impett, 1994). However, the most fundamental interaction with brass instruments is that between the player's lips and the mouthpiece. This has been variously measured using strain gauges (Mayer & Bertsch, 2005; Bianco, Freour, Cossette, Bevilacqua, & Caussé, 2012), and electrodes to determine the electrical conductance across the lips (Freour & Scavone, 2012).

Bowed Strings

Performance analysis of bowed string instruments is an active field of research, an overview of which can be found in (Overholt, 2014). A prominent example of work in this area is the Hyperbow project (Young, 2002). Developed at the MIT Media Lab, this system is comprised of several sensors integrated into a conventional violin bow. The continuous position is calculated using an electromagnetic field sensing technique involving a resistive strip along the length of the bow and an electrode antenna behind the bridge of the instrument. Acceleration on all 3 axes is obtained from two ADXL202 accelerometer devices, and the downward and lateral forces on the bow itself are measured using strain gauges. In collaboration with the Royal Academy of Music, a series of cello compositions was commissioned in which the physical gesture data from the Hyperbow is mapped to various parameters of accompanying technological systems, such as filter cutoff frequencies, delay depth and distortion (Young, Nunn, & Vassiliev, 2006).

A related study (Rasamimanana, Fléty, & Bevilacqua, 2006) at IRCAM employs a similar sensor configuration for the analysis and classification of three distinct violin bowing techniques (*Détaché*, *Martelé* and *Spiccato*). While both bow position and acceleration are measured, Linear Discriminant Analysis indicates that acceleration is the most salient parameter for bow stroke recognition. However, the position sensing approach might be beneficial as part of a technological practice tool, as maintaining an appropriate and consistent distance between the bow and the bridge can prove problematic for novice players.

The K-Bow (McMillen, 2008) is a Kevlar and carbon graphite bow which incorporates a grip sensor, a 3-axis accelerometer and measurement of bow hair tension, giving a detailed account of the interactions between performer, bow and instrument. Other sensing strategies in the context of bowed strings include optical bridge pickups to measure individual string vibration (Overholt, 2005); optical reflectance sensing for bow tracking (Pardue & McPherson, 2013); and finger position detection on the fingerboard using force-sensitive resistors (Grosshauser & Tröster, 2013), capacitive sensor strips (Grosshauser, Feese, & Tröster, 2013), and a custom linear potentiometer approach (Pardue, Nian, Harte, & McPherson, 2014).

Other Instruments

In (Kessous, Castet, & Arfib, 2006), a linear sensing method based on force-sensitive resistors (FSRs) is applied to a modified electric guitar neck to measure finger position and tactile pressure. Similarly, capacitive touch sensors have been incorporated into the fretboard of a classical guitar in order to study "expressiveness" in left hand technique (Guaus, Ozaslan, Palacios, & Arcos, 2010).

Capacitive sensing has also been employed in the context of piano-style keyboard instruments (McPherson & Kim, 2011). The TouchKeys system enables the augmentation of existing acoustic and electronic keyboards through the addition of unobtrusive multi-touch capacitive sensors to the tops of the keys (McPherson, 2012). By measuring the position and contact area of up to 3 touches per key, the traditionally discrete keyboard interface is extended to allow continuous control of multiple sonic parameters. In addition to providing novel techniques for musical expression, such an interface can also be useful in a pedagogical context to examine the subtle details of keyboard playing technique (MacRitchie & McPherson, 2015). A comprehensive review of continuous sensing strategies for keyboard instruments can be found in (McPherson, 2015).

2.1.3 Digital Technology in Traditional Musical Contexts

The design of digital technologies for specific musical contexts is explored in (Benford, Tolmie, Ahmed, Crabtree, & Rodden, 2012), which presents an ethnographic study of traditional Irish pub sessions. A detailed account of the etiquette by which such sessions operate is provided. For example, when selecting what to play, musicians will consider which styles are deemed appropriate in the current situation, which tunes others are likely to know, and what has already been played (repeating tunes is often seen as undesirable). Generally speaking, when a musician begins a tune, he or she is usually responsible for deciding the entire set, with changes between pieces being communicated by nods and the shouting of key signatures.

It is observed that while conventional musical notation is often unwelcome, and that overtly visible technology (such as amplification) is largely frowned upon, "everyday" electronic devices such as mobile phones are typically acceptable. It is suggested that in the context of traditional folk sessions, a carefully designed smartphone app might therefore be less conspicuous than a piece of paper. The authors conclude by stressing the importance of this notion, which they refer to as *situated discretion*, when developing tools for specific user groups. This highlights a central consideration in the design of digital musical interfaces in general; the technology should be as unobtrusive as possible, from both physical (i.e. not interfering with existing instrumental technique) and social perspectives.

An example of this situated discretion principle applied to the specific context of a celtic folk instrument is the Carolan Guitar (Benford, Hazzard, Chamberlain, & Xu, 2015). Carolan is a bespoke handmade acoustic guitar, adorned with ornate celtic knot-work patterns on the body, headstock and fretboard. These patterns are in fact digital *Artcodes* (Meese et al., 2013) which can be scanned using a custom application for mobile devices. The codes link to a range of online content (such as the maker's website, blogs documenting where and by whom the guitar has been played, and technical information concerning the battery and truss rod) with the aim of documenting the instrument's history and connecting it directly to its "digital footprint".

In (He, Kapur, & Carnegie, 2014), several challenges concerning the integration of technology with traditional Asian music are identified. It is noted that the status of some Asian instruments as objects of spiritual significance often serves to discourage researchers from performing physical modifications such as the addition of sensors. Language barriers are also an issue in this domain; even native speakers of the national language can face significant difficulties when seeking notation of the traditional repertoire, since such documentation (in so far as it exists at all) is often found only in modified or archaic dialects. Nonetheless, the authors suggest that through the development of culturally specific tools, technology can contribute to the preservation of Asian musical traditions by providing insights into the music, the instruments and the associated playing techniques in a universally comprehensible language.

McPherson and Kim (2012) discuss the difficulties associated with building a community around an augmentation of a traditional instrument. The article draws on observations from a case study involving several classically-trained composers and performers working with the *magnetic resonator piano* (MRP), an electronically augmented acoustic piano (McPherson, 2010). The authors assert the importance of allowing musicians to forge a personal artistic relationship with the sounds and playing techniques of the instrument. In the reported case study, the designer worked closely with six composers, using their creative feedback to make iterative developments to the MRP. This feedback was predominantly concerned with relaxing certain constraints (e.g. dynamic range, attack time and timbral control) in order to make the instrument more generically useful to a composer or performer wishing to exploit its expressive potential.

The article concludes with a set of general guidelines to assist DMI designers in building a community around their instrument. In addition to the iterative design process described above, the authors recommend that while a DMI should be sufficiently unique to provide a compelling reason for its use in the stead of a traditional instrument, the likelihood of widespread adoption by musicians is greatly increased when some relationship to existing techniques and skill-sets is maintained.

The McGill Digital Orchestra Project (Ferguson & Wanderley, 2009, 2010) explored the use of novel instruments in concert performance. A variety of new DMIs were developed. The designers of the interfaces worked in collaboration with expert players of traditional orchestral instruments, who provided ongoing feedback during the development process. Several new musical works were composed and performed over the course of the 3 year project. The authors propose that the ability for a DMI to reproduce a particular piece (including when played by different performers) is an appropriate metric by which to evaluate its effectiveness for composed ensemble performance, and that this contributes to its potential for adoption by new musicians. The issue of reproducibility is also addressed through the development of specific notation methods with which to transcribe the pieces written for the instruments.

2.1.4 Evaluation Strategies for Digital Music Technologies

While there is already a wealth of research into the design of digital musical instruments and interfaces, comparatively little work has been published with regard to the development of formal evaluation methods for such technologies. Accepted quantitative HCI metrics such as task completion rates can be problematic, as the creative and affective aspects of musical interaction cannot be easily measured.

That said, the use of task-based methods in this context has been investigated. In (Wanderley & Orio, 2002), the authors propose evaluation based on "maximally simple" musical tasks (e.g. the reproduction of arpeggios, trills, glissandi etc.), suggesting that this might allow for quantitative comparison between musical interfaces. This approach is founded on the somewhat contentious assertion that simplicity is a "general feature of musical tasks" (Orio, Schnell, & Wanderley, 2001), although it is acknowledged that this notion might seem "totally non-musical", and that such methods are envisaged as a "first step" in a comprehensive evaluation.

Certainly, there are aspects of some musical interfaces for which this approach could provide useful results. It seems reasonable that in terms of technological practice tools, assessing effectiveness and reliability in the completion of clearly defined tasks (e.g. recognition of a specific type of performance error) may indeed be appropriate.

Subsequent work has explored the use of the evaluation framework proposed in (Wanderley & Orio, 2002). The study presented in (Poepel, 2005) aims to compare the expressive potential of bowed string instruments based on a series of tasks relating to different aspects of musical expression. In (Kiefer, Collins, & Fitzpatrick, 2008) a task-based user study of a digital musical controller is carried out, and interviews with the participants are conducted. The authors report that while the quantitative results provided some objective support to opinions expressed in the discussions, the interview data yielded the most "interesting" findings in terms of unexpected issues with the interface and experimental setup.

Observations based on interview data of this sort are not uncommon in the literature relating to new musical instruments. However, it is often the case that the interviews are rather informally conducted, and only select quotations or broad overviews are provided. While this procedure can offer valuable insight during the design and development of a particular interface, it provides little analytical reliability in terms of repeatable, statistically significant results.

To address this, *discourse analysis* can be employed to study interview transcripts according to a formal, structured method (Stowell, Plumbley, & Bryan-

Kinns, 2008). Through a rigorous process of itemisation and association of the various entities described in the discourse, a comprehensive reconstruction of each participant's conceptualisation of the system under investigation can be obtained. In (Stowell, Robertson, Bryan-Kinns, & Plumbley, 2009), this approach is employed to evaluate a voice-controlled technological interface designed for use by beatboxers. The authors report that the discourse analysis illustrates in detail the interplay between concepts such as controllability and randomness in using the system, and that such results would be difficult to observe using other methods (e.g. questionnaires).

The second case study in (Stowell et al., 2009) describes a quantitative evaluation of the B-Keeper automatic rhythmic accompaniment system (Robertson & Plumbley, 2007) based on the widely known *Turing test* (Turing, 1950). Eleven professional and semi-professional drummers took part in the test, which involved playing along to a musical backing track. The tempo of the track could be kept constant, or adjusted dynamically to keep time with the drummer's own playing based on either the B-Keeper system, or a human listener tapping along. Participants were found to have some difficulty distinguishing whether the tempo-following was controlled by the B-Keeper or the human tapper. The authors note that this evaluation method is limited to situations in which the system is intended to emulate human performance in some way. In the context of technologies to assist in instrumental practice, it could be envisaged that such an approach might prove useful in comparing the analysis and feedback provided by the system to the observations of an expert human instructor.

In a recent review of proposed evaluation methods for digital musical instruments (Ó Modhráin, 2011), it is asserted that a number of different "stakeholders" (e.g. composer, performer, audience and manufacturer) are involved in the development and deployment of the interface, and that a comprehensive evaluation should consider each of these viewpoints. The article concludes by presenting a framework of approaches and the contexts (or stakeholder perspectives) in which they are a relevant measure of the instrument's effectiveness.

The evaluation strategies discussed above are largely concerned with entirely novel instruments. However, the goals of the technological developments presented in this thesis are somewhat different. Rather than assessing, for example, mapping strategies to maximise the expressive potential of a new interface with unfamiliar playing techniques, the primary aim in this case is conformance to certain aspects of traditional practice such that the system could be useful to, and accepted by, the Highland piping community.

In particular, with regard to the digital chanter hardware, it is important that the interface provides a sufficiently authentic physical and sonic facsimile of an acoustic chanter that it enables the user to practice skills and techniques that can then be transferred back to the traditional instrument. The pedagogical benefits of such an interface can then be fully exploited using software to provide analysis and insight into the player's performance which would be difficult or impossible to achieve using acoustic instruments alone. The following section provides a review of existing work in the field of digital tools for musical instrument tuition and practice.

2.2 Digital Technology in Music Education

It has been suggested (Percival, Wang, & Tzanetakis, 2007) that the use of up-to-date technologies to enhance musical instrument tuition and practice is not a new phenomenon. Mirrors, metronomes and tuning forks have long been familiar fixtures in the practice room. Since the advent of electronic recording devices, many tutors have exploited such tools to enable students to develop their critical listening skills by analysing their own recorded performance. More recently still, there has been a wealth of research into the use of computer-based systems to support musical instrument learning. This section provides a brief discussion of the potential benefits of digital technology in music education.

A study by the Office for Standards in Education (Ofsted) in which inspectors visited 52 schools around the UK highlights several ways in which technology can "enable attainment", "enhance progress" and "increase pupils' motivation" in music classrooms (Mills & Murray, 2000). It is noted that in this context the tools should not take over the role of teacher, but should instead be employed to help clarify conceptual information for the student. For example, in lessons concerning critical listening, tutors could adjust the level of certain parts of a multitrack audio piece in order to help pupils focus on musical features which were previously imperceptible. The authors also report the use of computer-based sequencers to produce backing tracks (e.g. the left hand ostinato of a piano piece), allowing the students to practice the right hand part separately while still being able to listen to and absorb the full sound of the piece as a whole.

Percival et al. (2007) identify three main areas in which Computer-Assisted Musical Instrument Tutoring (CAMIT) systems can assist the learning process:

supporting lessons with a tutor, enhancing the efficiency of solo practice, and increasing the student's motivation to play their instrument. In particular, the article asserts that objective self-testing tools to evaluate the player's execution of technical exercises (e.g. through measurement of pitch, timing, loudness or tone quality) can alleviate the inherent difficulty of self-evaluation faced by many inexperienced players. Moreover, the authors propose that a well-designed educational game tailored to the target audience (e.g. with rewards based on "levelling up" for younger users, or competitive scoring against others for older players) could generate enthusiasm for practice which would greatly outweigh the benefits of even the most sophisticated multimedia feedback system.

The idea that computers can be effective in providing guidance to students when practicing in the absence of an experienced instructor is echoed in (Hochenbaum & Kapur, 2013). The authors suggest that in order to allow meaningful feedback to be generated, the system should be able to analyse not only the sounds produced by the player, but also the physical actions by which they were created. To this end, the article argues that DMIs, either in the form of novel interfaces or augmented acoustic instruments, "will be elemental in the future of musical pedagogy and practice".

In the following section, the instructional strategies and learning theories associated with the domain of computer-assisted music education are considered. Discussions of specific research projects addressing technological support for solo instrumental practice, tuition and remote learning are presented in Sections 2.2.2, 2.2.3 and 2.2.4 respectively.

2.2.1 Instructional Strategies and Theories of Learning

In a review of computer-assisted music education systems at the turn of the last century (Brandão, Wiggins, & Pain, 1999), the authors frame such work in terms of a continuum between Computer Assisted Instruction (CAI) and Intelligent Tutoring Systems (ITS). In this article, CAI applications are defined as possessing "no explicit representation of the knowledge to be taught or ability to reason about it", and having no capacity to distinguish between different users. At the purest CAI end of the spectrum, the system will simply provide predefined responses to specific input from the student.

By contrast, an ITS is generally composed of three separate constituent parts: a *domain model*, which provides expert knowledge of the relevant subject matter; a *student model* to keep track of an individual student's development in terms of knowledge and capabilities; and a *teaching model* or *circular knowledge* system. This last component aims to reduce the difference between the expert domain knowledge and the model of the student's progress by applying one or more specific instructional strategies.

A separate review of Artificial Intelligence approaches to music eduction (Holland, 2000) observes that some ITS applications feature a fourth component, in the form of a specifically designed interactive user interface. This article also identifies the distinction between "well-formalised" educational domains (e.g. arithmetic) for which there are definite correct answers and criteria for success, and "open-ended" domains (i.e. subjects without obviously quantifiable goals). It is observed that musical activities generally fall into the latter category, and that in such cases the learner will often be required to *seek* problems as well as solve them.

Brandão et al. (1999) discuss the relationship between five common instructional strategies employed in ITS and CAI systems, and two contrasting theories of human learning, referred to as *connectionist* (or *behaviourist*) and *cognitive* approaches (Child, 1973). Connectionism is concerned with observable behaviour, which it sees as a direct response to a particular stimulus. This corresponds to the instructional strategies known as "programmed learning" (whereby the system presents frames of prepared material to the student, elicits a response, and provides pre-defined feedback) and "drill and practice" (continuous repetition of an activity or activities until the sequence is internalised) which are most closely associated with CAI applications such as the GUIDO aural training system (Hofstetter, 1981).

The cognitivist view of learning instead focusses on the development of a mental framework for understanding the various elements of a task, and the relationships between them. In (Brandão et al., 1999), this is linked to three instructional strategies: "Socratic dialogue", "coaching/monitoring" and "exploratory", the first two of which are commonly included in the teaching model component of typical ITS applications (Holland, 2000). The goal of Socratic dialogue is to prompt the student to recognise and rectify misconceptions in their understanding of the domain. The coaching/monitoring strategy is primarily concerned with maintaining the student's engagement with the activity, while following their progress and providing feedback on problem areas where necessary.

(Holland, 2000) asserts that in general, ITS applications assume an *objectivist* approach to knowledge (Vrasidas, 2000), and as such are best suited to formalisable tasks (e.g. learning rules for harmonisation). The article argues that for open-ended domains, a more exploratory instructional strategy is preferable. This corresponds to a *constructivist* view of learning; that is, that knowledge is constructed through the learner's encounters with their environment. The author's Harmony Space system (Holland, 1994) is an example of an interactive tool to promote explorative learning in the domain of tonal harmony. Users can manipulate musical entities (e.g. notes, chord sequences and modulations) on a grid-like interface based on a single principled spatial metaphor, allowing the musical effect of different operations to be rapidly investigated even by novice learners.

2.2.2 Digital Tools for Solo Instrumental Practice

The use and development of technological tools for musical instrument practice is an active field of research. A significant proportion of existing work in this area is concerned with piano pedagogy using MIDI input from a digital piano or keyboard, due at least in part to the MIDI protocol providing a simple means of capturing multiple aspects of a performance. In (Yokoo & Nagaoka, 1985), an automatic evaluation system is presented which allows visual comparison between student and expert keyboard performances in terms of tempo deviation. While the program is intended primarily to assist in solo practice, the authors note that the presence of a human instructor would help overcome certain limitations in the automated feedback; for example, system does not know which fingers were used and so can not diagnose fingering errors.

The Piano Tutor project (Dannenberg et al., 1990, 1993) is an interactive ITS tool to support solo piano practice, which combines score-following software and performance evaluation algorithms with extensive multimedia feedback to "create a natural dialogue with the student". The system incorporates a student model to log the progress of individual users, in order to provide a tailored curriculum according to the learner's knowledge and abilities. The teaching model employs instructional approaches based on the "drill and practice" and "coaching/mentoring" strategies described in Section 2.2.1. In an extensive user study, the system was found to present a greater number of lessons to less experienced players over the course of the curriculum, which suggests that the student model was effective in determining the ability of the pupil.

Goebl and Widmer (2006) propose an approach to recognise and evaluate certain "well-defined sub-aspects" of piano playing using a MIDI keyboard. The system can detect recurring patterns (e.g. Alberti bass passages) and provide real-time visualisation of differences in pitch, synchrony and dynamics. A range of display options are described, including graphical plots of temporal and harmonic deviations, and an "acoustic piano roll" representation which extends the standard piano roll to include volume and pedal interaction data.

Robine and Lagrange (2006) present a highly focussed study in which more than 30 alto saxophonists were instructed to play five separate notes with specified dynamics, including one with vibrato. By analysing the evolution of various spectral parameters of the sound across the duration of each note, the system was found to provide an accurate assessment of the overall ability of the performers, as determined by a professional instructor. The authors suggest that such a tool would be valuable to help students gauge their progress when practicing without a human teacher.

The Open Orchestra Project (Olmos et al., 2012) is an "ensemble simulator" for orchestral and big band training. The system provides an audiovisual recording of a professional ensemble (taken from the perspective of an ensemble member), and captures the student's performance as they practice along with the video. Once the piece is finished, the computer provides a comparison of the differences between the student's recording and an expert musician playing the same part. In (Knight, Boulliot, & Cooperstock, 2012), the authors investigate the effect of visualisations of articulation and dynamics in making subjective assessments of the student's playing compared to the reference performance.

The Digital Violin Tutor (Yin, Wang, & Hsu, 2005), intended primarily as a solo practice tool to provide feedback in the absence of an instructor, employs a transcription algorithm to visualise and compare the student's playing with an existing score, or earlier recording made by the teacher. The system presented in (Hochenbaum & Kapur, 2013) also considers bowed string pedagogy, using a custom-built augmented zither (the *Ezither*) and accompanying software to capture audio and sensor data. The article describes an extended study in which a novice performer practiced using the instrument over a seven month period. The system provides visualisations to illustrate how various aspects of the player's technique (e.g. consistency of different bow strokes) evolves over time.

The IMUTUS tool (Fober et al., 2004; Raptis et al., 2005) is an ITS which provides automated analysis and evaluation of students' recorder performances. The system incorporates a user-controllable function to determine which types of mistakes should be prioritised in the feedback, in order to avoid overwhelming the learner with a dauntingly long list of errors after each attempt (Schoonderwaldt, Askenfelt, & Hansen, 2005). IMUTUS also features a distance learning component, in the form of a repository for users to access new context, and an online forum for students to upload their performances and request feedback from human instructors. The VEMUS project (Fober, Letz, & Orlarey, 2007) extends the work from IMUTUS to consider other wind instruments such as flute, clarinet and saxophone. The system aims to support solo practice, instrumental instruction and distance learning, as does the MEAWS application (Percival et al., 2007) which is aimed at both wind and string family instruments.

One example of technological support for musical learning in a group context is the Family Ensemble (FE) system (Oshima, Nishimoto, & Suzuki, 2004). The authors assert that duo play (e.g. playing together with a teacher) is highly beneficial in learning the piano, and that attempting to replicate this with "minus-one" software (i.e. computer programs to provide automatic accompaniment) can prevent the student from "acquiring the skill of cooperative performance that is essential for ensembles".

To address this issue, the FE system is intended to allow parents of children learning the piano to play along with them, despite having little or no practical musical experience. Using a score-following algorithm on the child's performance, FE automatically corrects any pitch mistakes made by the parent, allowing them to focus on the rhythmic and expressive aspects of the piece. The system prevents the parent's part from advancing ahead of the child, ensuring that the accompaniment is more sympathetic than an automated backing track. It should be noted that FE is not directly supporting the child (i.e. the person actually learning the instrument) as the authors believe this would "detract from the learning process".

User testing with the FE system investigates the mistakes made by the child in terms of the three classes of performance error defined in (Bloch & Dannenberg, 1985): *extra* notes, *wrong* notes, or *missing* notes. However, the target users in (Bloch & Dannenberg, 1985) are already assumed to be expert performers. In the case of FE, it was observed that a fourth type of error, *stopping and replaying* a given note or phrase, occurred significantly more often than the others among the inexperienced pianists.

2.2.3 Digital Tools to Support Instrumental Instruction

The distinction between tools to support solo practice and those designed for the lesson environment is not always entirely clear. While there is certainly some similarity between the work described in the Section 2.2.2 and that discussed below, this section focusses on systems for which the authors envisage some degree of interpretation of the data by an expert instructor, rather than relying solely on the machine to provide feedback directly to the student.

The *pianoFORTE* system (Smoliar, Waterworth, & Kellock, 1995) produces visualisations of tempo, articulation and dynamics of a performance in the form of an annotated musical score. In addressing the development of tools to assist in one-to-one instrumental instruction, the authors assert that the aim is not to automate the teacher, but to facilitate the "difficult communication process" through which the instructor attempts to describe the subtleties of expressive interpretation beyond simply playing the correct notes.

The *MIDIator* tool (Shirmohammadi, Khanafar, & Comeau, 2006) also captures piano performance via MIDI, allowing quantitative comparison between separate renditions of the same piece by producing graphs to illustrate variations in tempo, note velocity, duration and articulation. The SYSSOMO system (Hadjakos, Aitenbichler, & Mühlhäuser, 2008) uses MIDI, raw audio, video and motion data from accelerometer and gyroscope sensors to capture a comprehensive record of a pianist's movements. A score following algorithm is employed to align and superimpose two performances with different tempi, enabling direct visual comparison between the playing of instructor and student.

In (Ng et al., 2007), motion capture equipment is used in conjunction with standard video and audio recording to create the *3D Augmented Mirror*, a pedagogical tool to help the tutor "identify, illustrate and explain certain issues" in bowed string instrument practice. The performance data can be played back and displayed in a variety of visualisation formats depending on the current focus of the lesson, and sonification techniques (e.g. to provide real-time aural feedback about the player's bow angle) are investigated. 3D visualisation is also used in (Mora, Lee, Comeau, Shirmohammadi, & El Saddik, 2006) to display variations in playing posture between student and expert pianists.

The approach presented in (Bevilacqua, Guédy, Schnell, Fléty, & Leroy, 2007) employs a wireless accelerometer/gyroscope motion sensor configuration in a music school class room to detect the physical gestures of pupils "conducting" along to a piece of music. These are then compared to pre-recorded patterns and identified in real time using a method based on time warping and Hidden Markov Models.

Other research has directly examined the raw audio signal produced by an acoustic instrument in order to determine information about the player's technique; this is referred to as "indirect acquisition" of performance gesture (Traube, Depalle, & Wanderley, 2003). Ferguson, Vande Moere, and Cabrera (2005) explore real-time visualisation techniques for sonic features such as harmonic content, noisiness, loudness and fine pitch, with the aim of increasing the efficiency of the "feedback loop" between student and instructor in traditional lessons. Dixon, Goebl, and Widmer (2002) provide real-time visualisation of "musical expression" in terms of changes in tempo and dynamics, which the authors suggest could be useful to conservatory music tutors as an additional tool to examine the subtle details of a student's playing.

2.2.4 Networked Learning Environments

In addition to the multi-modal systems mentioned previously (Fober et al., 2004, 2007; Percival et al., 2007) which include distance learning components, some recent research has focussed specifically on networked music learning applications. This section provides a brief overview of some significant work in this domain.

Remote tuition via video conferencing can be useful in enabling regular lessons with the same instructor when co-present sessions are not possible, and are already used by many professional tutors, particularly in countries where students may live in isolated areas such as Australia (Tait & Blaiklock, 2005) and Finland (Juntunen, Ruismäki, & Ruokonen, 2011). Duffy et al. (2012) present a multi-camera system for remote instrumental tuition, which allows the instructor to select between different views of the pupil using a tablet-based control application.

An ethnographic study of co-present lessons found that non-verbal teacher-student interaction in the shared space (e.g. joint reference to the same physical score) is an essential element of one-to-one music tuition (Duffy & Healey, 2012). Moreover, the authors report that synchronous activity (e.g. singing or playing together) accounted for less than 15% of the total lesson time. This suggests that technical considerations such as latency and audio-visual quality are less critical to the success of video conference teaching than providing support for the kinds of communicative activity that underpins traditional lessons.

The iSCORE system (Upitis, Brook, & Abrami, 2012) is a web-based tool, developed to support remote music teaching and learning. The platform is based around the theory of *self-regulation* (Zimmerman, 2000), a cyclical process of forethought, performance or volitional control, and self-reflection. Students can upload their performances to iSCORE in order to obtain feedback either from their teacher or other learners. A student advisory committee of iSCORE users identified several key strengths of the system, noting in particular that it provides the benefits of social interaction with peers (such as enabling immediate and diverse feedback, and encouraging critical listening and thinking) within the context of a more focussed environment than generic social networks.

The PRAISE project (Practice and peRformance Analysis Inspiring Social Education) combines the concept of a music education centred social network with automatic audio and gesture analysis tools, and intelligent pedagogical agents to provide a multi-modal virtual learning environment (Yee-King & d'Inverno, 2014). Teachers can create specific lesson plans and tasks, which pupils can access online and practice in their own time. Peer feedback can be provided for uploaded recordings on a timeline with multiple layers (Brenton et al., 2014), which the authors suggest encourages more specific and ongoing discussion than a single-layered comment function (e.g. Soundcloud).

In addition to subjective appraisal by tutors and other students, performances can be assessed using a variety of automatic analysis tools. These are specified by the instructor during the creation of the lesson plan, and include algorithms to detect a range of temporal and harmonic features such as arpeggios, note anticipations and melody note choice for the current chord. The system can provide visualisations of divergences from an exemplar performance uploaded by the tutor, and also features a reflexive comparison function to examine how a student's progress with a particular piece develops over time.

2.3 Summary

This chapter has reviewed and discussed the relevant literature which provides the background for the work presented in this thesis. In Section 2.1, the main commercially available digital bagpipe chanters are described, and their limitations as practice tools are identified; namely their discrete sensing strategies, lack of air pressure control, and the fact that they make no distinction between correct and false fingerings. This suggests that existing electronic chanters do not provide an effective replica of the acoustic original for the purpose of acquiring technique. It is also observed that while software applications have been developed to assist in the process of notating GHB music, these do not support automatic transcription from user input.

An overview of continuous sensing strategies employed in DMI design is given, and the issues involved with developing technologies for traditional music communities are considered. In particular, the importance of adhering to accepted cultural conventions is asserted (Benford et al., 2012). In Chapter 3, a new digital chanter interface is presented which uses continuous optical reflectance and breath pressure sensing approaches (as described in Section 2.1.2) to address the disadvantages of existing electronic bagpipe hardware.

Section 2.2 identifies three main areas in which computer-based technologies can support musical instrument learning (Percival et al., 2007): as illustrative tools for use in lessons with a human instructor; as automatic analysis systems to assist the learner during solo practice; and by increasing pupils' motivation (e.g. through educational games). It is noted that traditional CAI and ITS applications are best suited to well-defined domains (Holland, 2000). Several aspects of GHB technique are highly formalised, in particular ornamentation and fingering. Chapter 4 presents an algorithm for automatic recognition and analysis of Highland piping embellishments to assist the student's technical development, and counter the inherent difficulty of self-evaluation faced by inexperienced musicians in the absence of an instructor (Percival et al., 2007).

More open-ended musical domains (e.g. expressive rhythmic phrasing) are less suited to automated analysis. To address such aspects of GHB practice, this thesis follows the approach of (Smoliar et al., 1995); rather than automate the tutor, the aim is to augment the traditional lesson environment by providing tools to assist the instructor in communicating "the subtleties of interpretation" to the student. To this end, a complete GUI application to support both solo practice and one-to-one tuition is presented in Chapter 5. This chapter also describes a game interface to increase motivation for practice among younger students, providing numerical scores based on correct execution of GHB technique. In this way, the system aims to address all three of the areas identified in (Percival et al., 2007) by which digital technology can contribute to musical instrument learning.

Chapter 3

Digital Chanter Hardware

This chapter describes the development of a digital bagpipe chanter interface, which forms the hardware component of the complete Highland piping practice system. Section 3.1 describes an initial prototype developed during the early stages of this work, which was first presented in (D. W. H. Menzies & McPherson, 2012). The final interface used in the later chapters of this thesis, which provides a significantly improved physical playing experience, is discussed in Section 3.2. The audio output of the digital chanter employs a looping playback approach using samples from acoustic bagpipe recordings; this is described in Section 3.3.

3.1 Initial Prototype

The purpose of the chanter interface is to detect the performer's finger movements quickly and accurately, and to send this data to the audio software via USB. This section describes the initial prototype developed during this project, which was first presented in (D. W. H. Menzies & McPherson, 2012). The complete chanter is shown in Figure 3.1.

As discussed in 2.1.1, commercially available digital bagpipe chanters generally use binary capacitive touch-pads in place of the tone holes. Although modern playing techniques involving partial or gradual uncovering of holes are not used in traditional piping, a sensing strategy that provides a continuous range of values indicating the extent to which a given hole is covered would deliver a more accurate model of the tone holes on an acoustic chanter. Previous approaches have achieved this using arrays of capacitive touch-switches (Cannon et al., 2003)

Figure 3.1: Initial prototype of electronic chanter interface being played.

or photoresistors (Kirk & Leider, 2007). However, these strategies are susceptible to variations in skin dryness and ambient light respectively. Moreover, the physical playing experience should be as similar as possible to an acoustic chanter, hence pressure-based sensors (e.g. force sensitive resistors) would not be appropriate in this context.

To address these issues, the initial electronic chanter prototype employs a robust infrared (IR) sensing system. For each hole, this consists of an IR LED and a photodiode, between which a constant IR beam exists (Figure 3.2). When the beam is interrupted by the player's finger, a continuous change in the voltage V_{out} can be measured. The resistor values $R_1 = 100\Omega$ and $R_2 = 10k\Omega$ were selected such that the full range for each sensor corresponds to approximately 150 discrete levels. Figure 3.3 shows a close-up photo of this sensor configuration.

The 16MHz ATmega328 microcontroller polls the eight input pins, and transmits the raw sensor data to the host computer via USB at a baud rate of 115200 bit/s. This configuration does not introduce any audible latency, allowing a degree of musical intricacy comparable to that of a traditional bagpipe chanter.

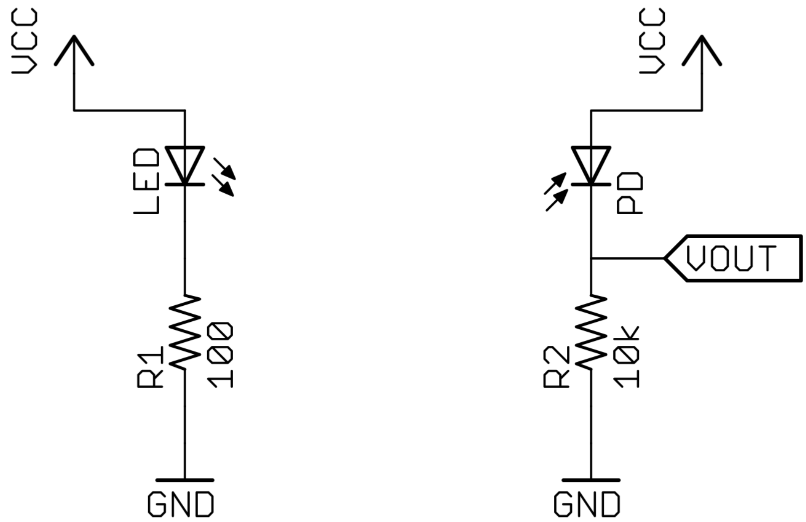


Figure 3.2: Single infrared sensor circuit for initial chanter prototype.

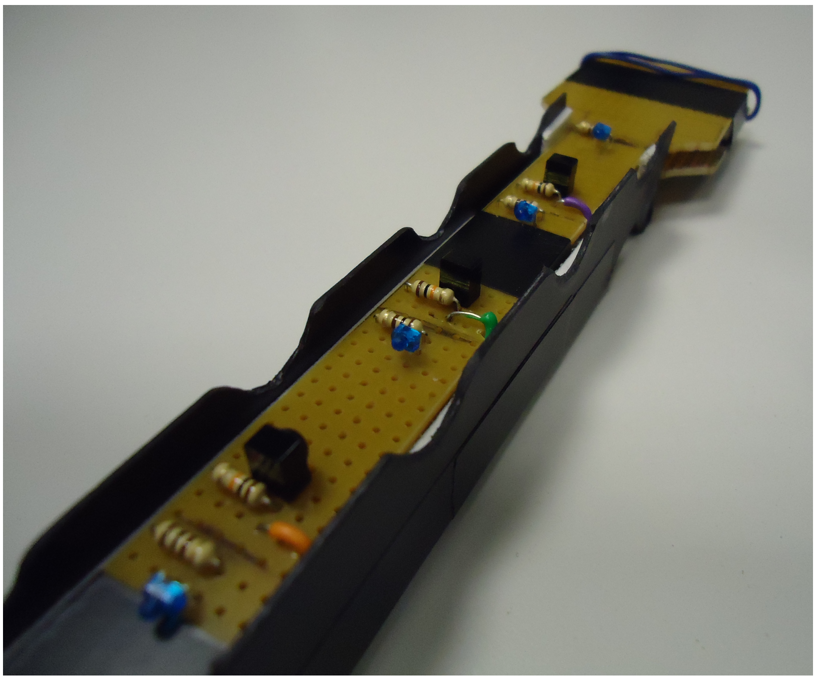


Figure 3.3: Close-up of sensor configuration for initial chanter prototype.

3.2 Refined Interface

The original electronic chanter described in Section 3.1 was successful in providing a continuous analogue reading for each hole. However, the physical construction of this prototype led to a somewhat unnatural playing experience, primarily as a result of being built using strip-board and through-hole components. The spacing between the sensors was dictated by practical layout constraints, and the requirement that the player's fingers sit between the IR emitter and detector prevented the board from being housed in a cylindrical shell. This interface was therefore deemed unsuitable for use as a practice tool, necessitating the development of an improved design.

One of the primary concerns when developing the refined hardware was to ensure that the physical playing experience be as similar as possible to a traditional Highland bagpipe chanter. To achieve this, a custom printed circuit board (PCB) was designed using a sensing strategy based on IR reflectance (McPherson, 2013). This provides continuous, contact-free measurement of the player's finger movements while allowing the board to be mounted inside a cylindrical casing with real holes, the spacing of which was chosen to mirror that of an acoustic chanter. The technical implementation of this tone hole sensing approach is discussed in Section 3.2.1. The improved interface also incorporates an air pressure sensor in place of the chanter reed, as described in Section 3.2.2.

3.2.1 Tone Hole Sensing Strategy

The final digital chanter interface uses a near-field optical reflectance sensing approach, based on the implementation described in (McPherson, 2013). The PCB features an integrated IR reflectance sensor, the Fairchild Semiconductor QRE1113GR (Figure 3.4), for each of the eight tone holes. This sensor is comprised of an IR LED and phototransistor in a single package, both directed upwards. When an object comes within range of the sensor, the IR radiation from the LED is reflected back and detected by the phototransistor, as illustrated in Figure 3.5. This allows the proximity of the player's finger to the sensor to be measured with a high degree of precision.

The data sheet for the QRE1113GR indicates a peak in the phototransistor collector current for a reflecting object located roughly 0.5-0.6mm from the surface of the sensor; that is, objects closer than this distance would result in a lower collector current, and hence could not be accurately distinguished from a more

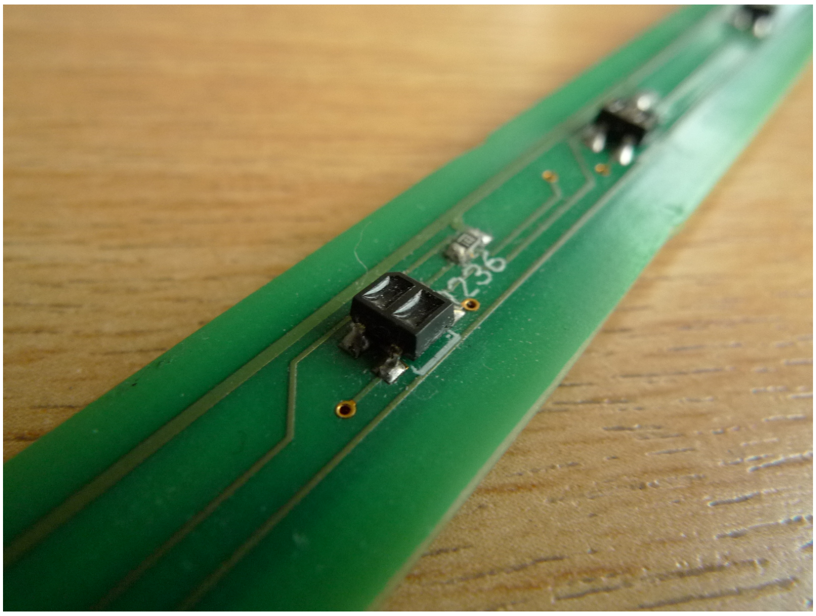


Figure 3.4: Close-up of PCB showing QRE1113GR infrared reflectance sensor.

distant object. In practice however, this effect does not present problems, as the player's finger is kept approximately 2mm from the sensor by the exterior of the chanter. Empirical measurement suggests that the sensors provide useful results for distances up to around 20mm, which is more than sufficient for the purposes of measuring tone hole coverage on the digital chanter interface.

Figure 3.6 shows a schematic of the sensor configuration. The eight tone hole sensors are grouped into pairs, and the collector pins of each phototransistor are connected to the inverting input of an operational amplifier. The op-amp feedback ensures that the collector voltage is fixed at VREF1. This provides a faster response time than a simple pull-up resistor circuit by alleviating the effect of parasitic capacitance in the phototransistor. The cathode pins of the LEDs are connected to one of two output pins on the microcontroller (labelled LEDOUT0 and LEDOUT1). These are used to turn the LEDs on and off, allowing the two sensors to share an op-amp channel. Figure 3.7 depicts the complete PCB layout, and a close-up photo of the end sections of the board is shown in Figure 3.8.

For the interface to be effective in accurately measuring the player's finger movements, it is important that the sensor readings are as stable and reliable as possible. Each of the IR sensors is therefore read eight times during every millisecond period and an average taken to reduce the effect of inaccuracies caused by mo-

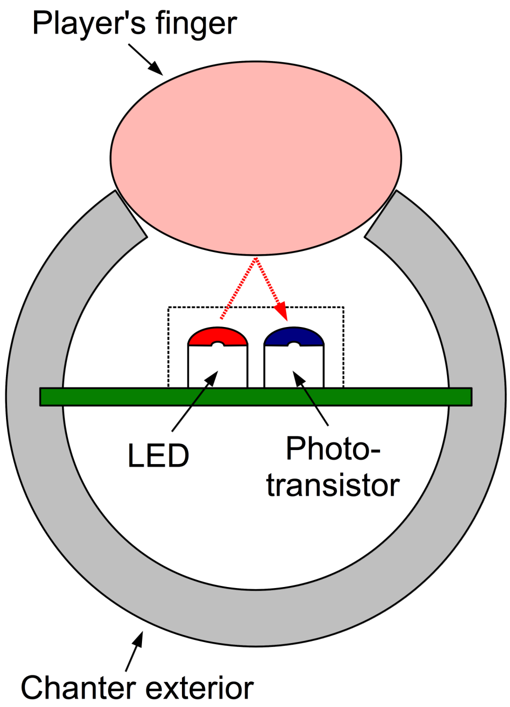


Figure 3.5: Cross section of digital chanter illustrating optical reflectance sensing approach.

mentary fluctuations. Since the sensing strategy is based on optical reflectance, it is also necessary to account for variations in ambient light. By measuring the output of each sensor with the LED off directly after each reading, an indication of the current background conditions is obtained. This measurement is subtracted from the original sensor reading, ensuring that the final value is robust to environmental interference.

The sensors provide a continuous analogue reading for each hole on the chanter, representing the extent to which the hole is covered by the player's finger. Since the practices of half-covering holes and sliding between notes are entirely absent from traditional Highland piping, the remainder of this thesis uses a simple thresholding approach to determine whether each hole is open or closed, the implementation of which is described in Chapter 5. However, the continuous sensing capabilities of the hardware have already been explored in the context of extended techniques which would not be possible using an acoustic chanter, such

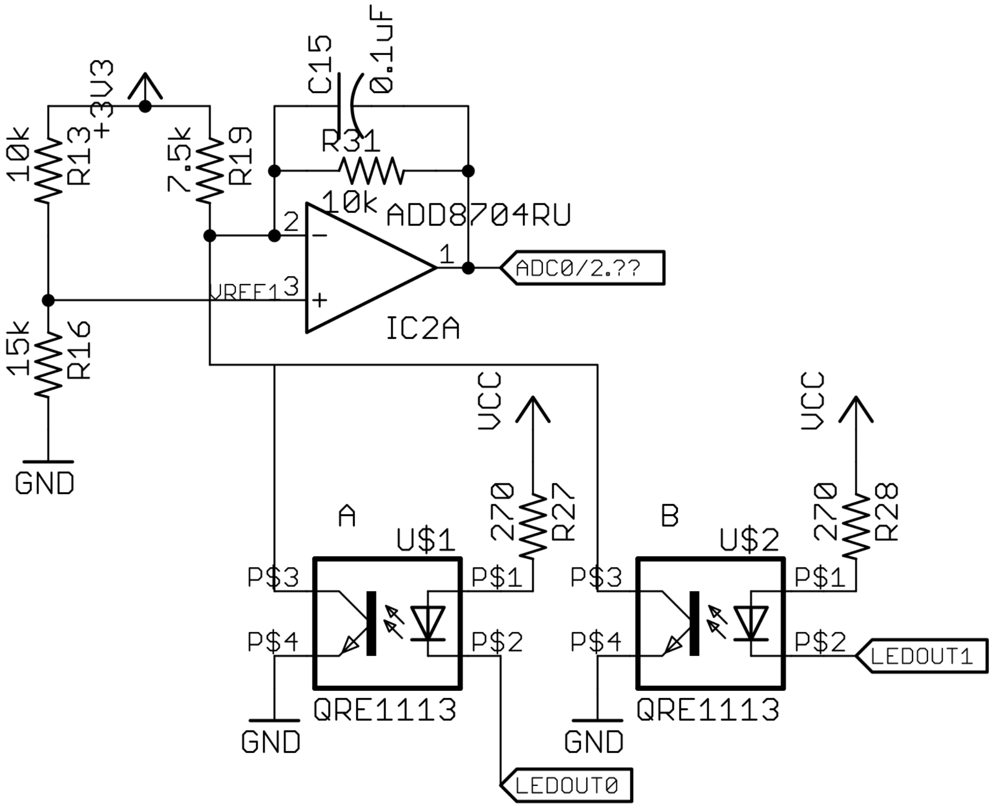


Figure 3.6: Schematic showing two QRE1113 sensors connected to one op-amp channel.

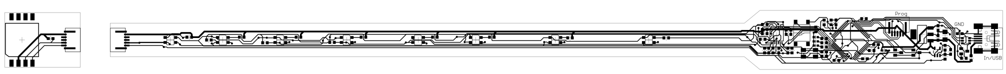


Figure 3.7: Complete layout of electronic chanter PCB, including small additional board for pressure sensor (left of image).

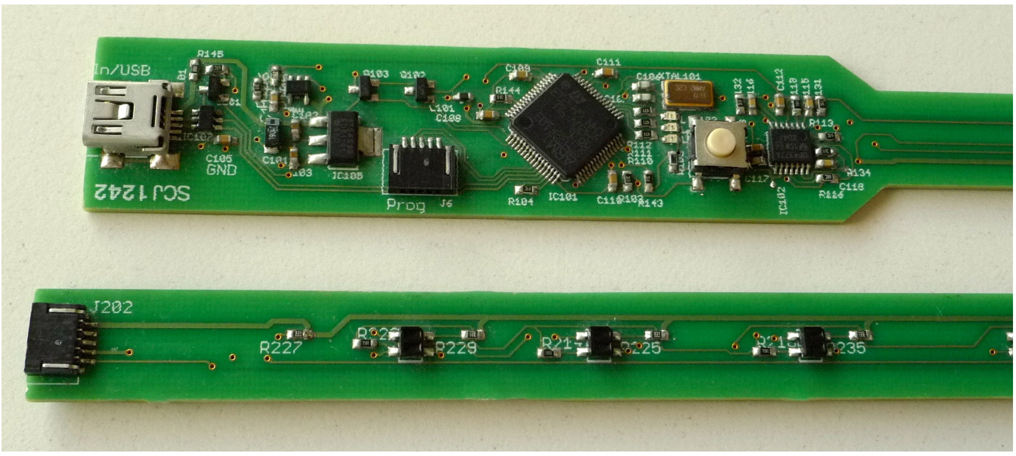


Figure 3.8: End sections of two chanter PCBs.

as polyphony and wah-wah effects[1]. Moreover, the sound generation software could be readily adapted to implement pitch bending using the continuous sensor values, either by extending the current sample-based approach (described in Section 3.3) to incorporate linear/cubic interpolation between samples, or through the development of a physical model applying recent work on modelling of double reeds (Vergez, Almeida, Caussé, & Rodet, 2003), conical bores (Scavone, 2002) and tone hole coverage (Scavone & Cook, 1998).

3.2.2 Air Pressure Sensor

In addition to the intricate fingering technique needed to reproduce a melody on the chanter, the GHB requires a steady flow of air through the chanter and drone reeds. This involves applying a constant pressure to the bag with the arm, and a significant degree of physical exertion to keep the bag filled with air. These essential aspects of bagpipe playing cannot be addressed using a standard practice chanter (Section 1.2.1.2), and thus regular practice sessions on a full set of pipes are traditionally required to maintain the necessary endurance. However, the high sound intensity levels involved can render this impractical for many pipers (e.g. those living in urban areas).

Therefore, a technological system that allows the user to work on the breathing and arm pressure elements of GHB technique at any volume (or wearing headphones) could provide significant benefit to the piping community. To achieve this, the digital chanter incorporates a Freescale Semiconductor MPXV5010 pres-

[1] `https://www.youtube.com/watch?v=urqjewHR-GQ`

sure sensor, as used in (Scavone, 2003). The sensor is mounted on a small additional PCB (shown on the far left of Figure 3.7), and the chanter exterior incorporates two small holes for the air to escape as it would through a conventional chanter reed. By closing off the drones of a standard set of pipes using stoppers and inserting the electronic interface into the bag in place of an acoustic chanter, the player can control the instrument using exactly the same physical interactions as with a traditional GHB.

This provides a complete and realistic playing experience, and allows the user to practice all aspects of Highland piping technique without any acoustic sound being produced. Moreover, the pressure at which the drones and chanter sounds are activated can be specified and modified in the software, enabling the player to adjust the strength of the virtual "reed" and progressively develop stamina.

3.2.3 Microcontroller Processing

The chanter PCB incorporates an ARM 32-bit Cortex-M3 microcontroller which gathers and processes the raw sensor data before transmitting it to the computer. The serial communication uses the USB Communications Device Class (USB CDC) protocol. The interface sends one complete message via USB every millisecond, providing accurate temporal information about the player's performance. For each message, the device generates a frame number in milliseconds using the onboard clock. Since such frame numbers are independent of the system clock on the host computer, these can be used by the final application to detect whether any frames have been dropped or delayed during transmission over USB. This allows the duration of short notes to be precisely determined.

Every complete message from the digital chanter is 20 bytes long, and is comprised of the millisecond frame number and nine sensor values (2 bytes each) in a packed binary representation. For each byte, the bottom 7 bits are used for data (giving 16384 possible discrete levels for each value), and the top bit is employed as a flag to indicate the start of a complete message: only the first byte in a message has a 1 in the top bit. This allows the host application to determine the beginning of each message from the incoming stream of bytes.

3.2.4 Physical Construction

In order for the physical feel of the interface to be as realistic as possible, the complete PCBs are enclosed in a 3D printed chanter exterior, as shown in Figure

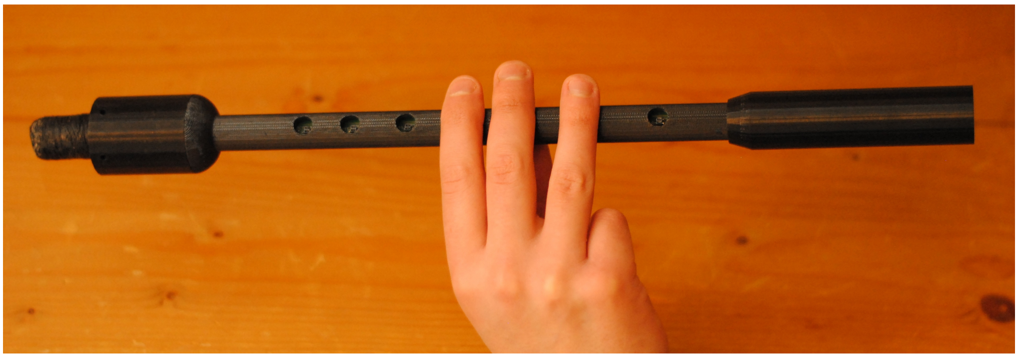


Figure 3.9: Complete digital chanter hardware in 3D printed chanter exterior.

3.9. This is designed in three parts which fit together around the board: a top section which contains holes for air flow and a stock for insertion into a traditional GHB set; a slim middle segment with the eight holes for the player's fingers, and a wider bottom portion which houses the microcontroller and associated circuitry, and the USB port (Figure 3.10). The 3D models of these components are depicted in Figure 3.11(a), (b) and (c) respectively. The bottom and middle sections incorporate a slot into which the PCB is inserted to hold it in place, as shown in Figure 3.12. The finger holes are 8.6mm in diameter, and are arranged according to the hole spacing on an acoustic chanter (Figure 3.13).

The smaller PCB for the pressure sensor fits into the wide end of the middle section (Figure 3.11(b)), and is connected to the main board by a ribbon cable. This section is then carefully sealed with insulation tape, such that only the pressure sensor nozzle protrudes, preventing any moist air from the bag reaching the electronic circuitry. However, for the interface to provide an accurate impression of the air flow in a traditional chanter, the air must be allowed to escape rather than be trapped in the bag. This is achieved using the top section of the 3D printed chanter exterior, which features a stock for insertion into a standard GHB (Figure 3.14), and internal channels through which the air can flow from the bag to the outside world. The 3D model for this component is shown in Figure 3.15, including a transparent view to illustrate the internal dimensions. Figure 3.16 shows the complete chanter being played as part of a full GHB set.

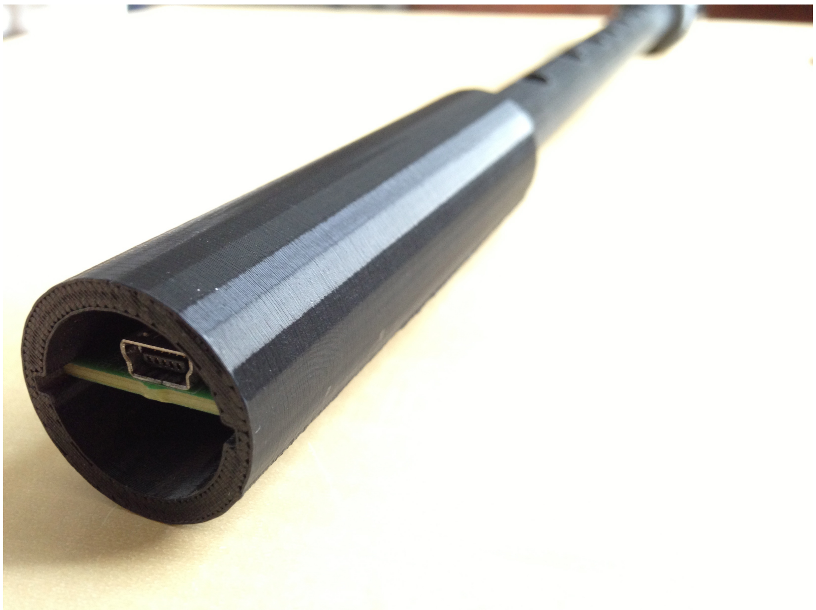


Figure 3.10: Bottom of complete digital chanter showing connection for USB cable.

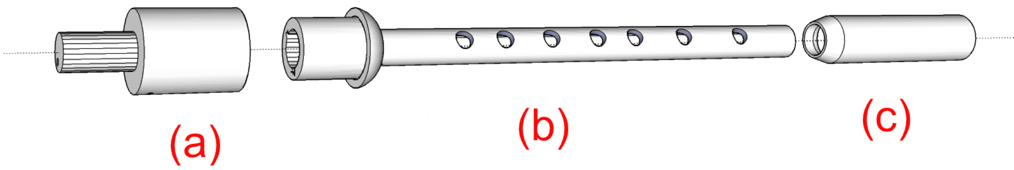


Figure 3.11: 3D model of chanter exterior components: (a) top section to house pressure sensor, (b) middle section incorporating finger holes, and (c) bottom section containing microcontroller circuitry.

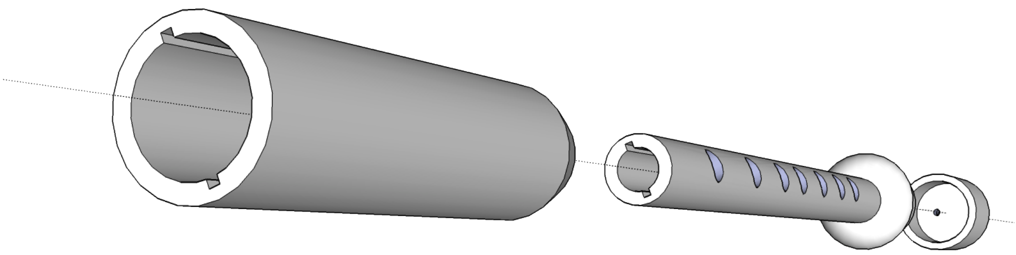


Figure 3.12: Chanter exterior 3D model showing slot for PCB in bottom and middle sections.

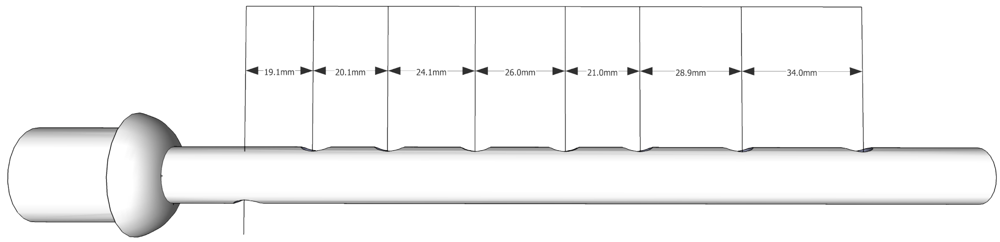
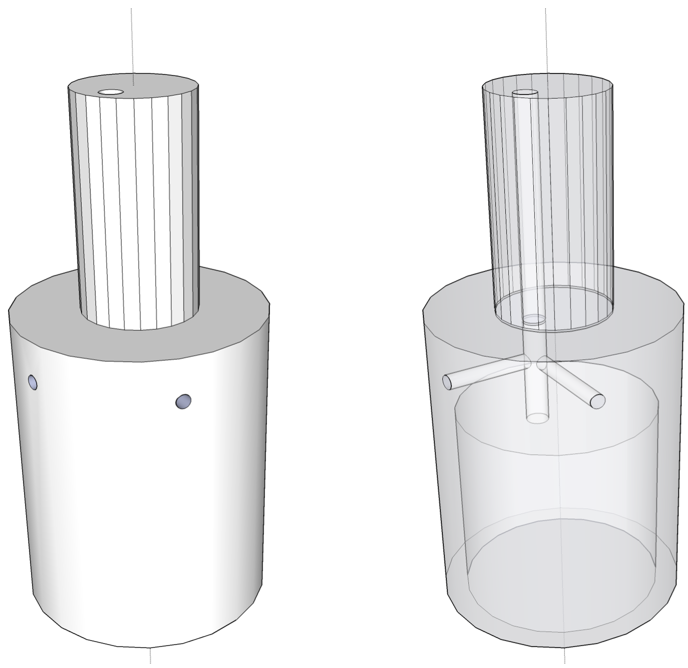


Figure 3.13: Middle section of chanter exterior 3D model showing hole spacing.

Figure 3.14: Top of digital chanter showing stock for insertion into acoustic GHB.



(a) (b)

Figure 3.15: Top section of chanter 3D model as (a) solid object, and (b) transparent view showing internal channels for air flow.

3.3 Sound Generation Software

The audio output for the digital chanter is generated using a standalone application written in the SuperCollider programming language (McCartney, 2002). The system is based on a sample looping approach, using excerpts from acoustic bagpipe recordings. Each note on a standard GHB chanter was recorded individually using an AKG C414 condenser microphone, as were the three separate drone pipes. For every pitch in the scale, a short selection was extracted at the individual sample level, corresponding to several complete repetitions of the particular waveform of the note. The waveform and resulting spectrogram for High A are shown in Figures 3.17 and 3.18 respectively. These audio files can then be looped indefinitely, providing a highly convincing representation of the distinctly stationary characteristic sound of the bagpipes. The recording and waveform selection process was then repeated for a set of traditional Scottish smallpipes (a smaller, quieter bagpipe which uses identical fingerings to the GHB and sounds approximately 13 semitones lower).

Figure 3.16: Final digital chanter interface incorporated into acoustic GHB set.

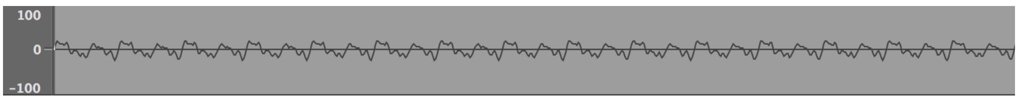


Figure 3.17: Waveform for High A audio sample.

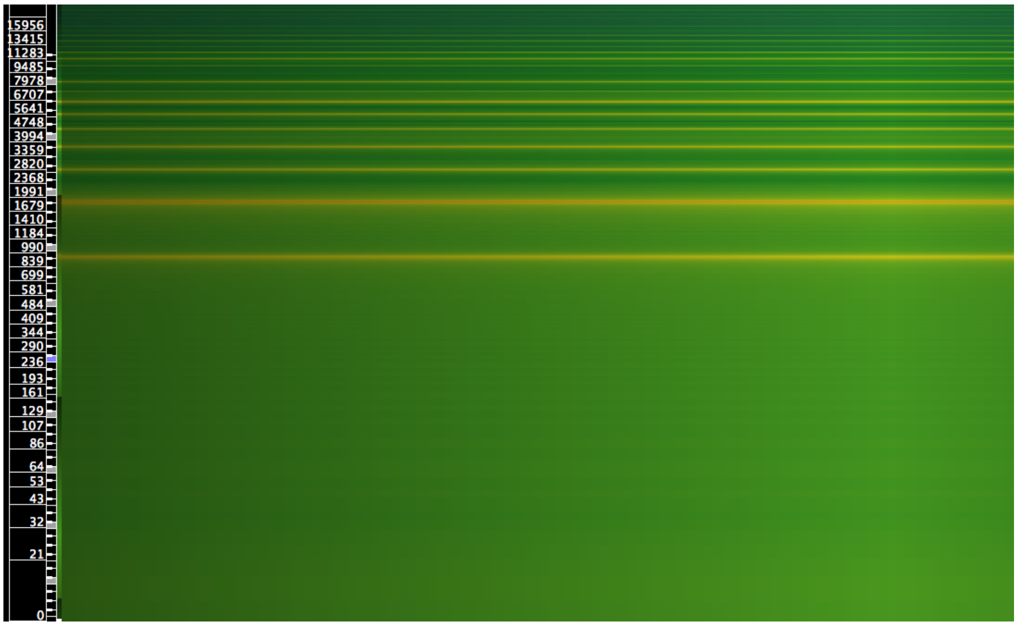


Figure 3.18: Spectrogram for High A audio sample.

3.4 Conclusions

This chapter has described the design and implementation of the digital chanter interface which forms the physical hardware component of the complete system developed during this project. Informal testing with expert bagpipers throughout the development process indicated that both the physical playing experience and the audio output were found to be realistic. One professional piper said of the interface *"It feels great . . . it's super accurate. That's the thing with those normal electronic sorts of ones [capacitive touch switches], they never quite work . . . It feels like a bagpipe; the airflow feels the same too."* Another experienced player reported that the chanter had a *"lovely crisp sound"* and that *"the drones sound great"*. While the remainder of this work focuses on traditional piping technique and hence does not exploit the continuous sensing capabilities of the interface for pitch bending or extended techniques, these could be readily implemented in the future. In the following chapter, the chanter is used to obtain detailed recordings of performances by pipers with a wide range of experience, in order to study the ornamentation techniques that are a central aspect of the Highland piping tradition.

Chapter 4

Automatic Recognition and Analysis of Highland Piping Ornamentation

This chapter concerns the development of an algorithm for the automatic recognition and evaluation of Highland piping ornamentation in performances recorded using the digital chanter interface. Section 4.3 describes a rule-based approach to this task, first presented in (D. W. H. Menzies & McPherson, 2012). An improved method based on Dynamic Time Warping (DTW) is presented in Section 4.4. In Section 4.5, the two algorithms are evaluated on a dataset of 30 recordings by expert and student pipers, and the DTW method is shown to provide a significant improvement in performance (D. W. H. Menzies & McPherson, 2015). The parameter settings of the DTW algorithm are tested extensively in Section 4.6, leading to an optimal configuration which further improves the recognition of embellishments performed by early stage players. Lastly, Section 4.7 presents a preliminary development which demonstrates the potential of the ornament recognition algorithm for automatic transcription of bagpipe music, a hitherto unexplored endeavour, and one which could be of considerable benefit to the piping community.

4.1 Motivation

Ornamentation is a fundamental element of Highland piping. Even the simplest bagpipe music requires the player to be familiar with at least the basic embellishments such as *gracenotes* and *strikes*, with complex multi-note ornaments (e.g. the *taorluath* and *birl*) quickly becoming necessary as more challenging tunes are encountered.

To the novice piper, the task of learning the diverse array of Highland piping embellishments can be both daunting and frustrating. Significant patience is needed even to remember the exact sequence of gracenotes in each ornament; more still to reproduce them consistently and with the required meticulous precision.

This is further compounded by the rapidity with which the movements are performed; to the untrained ear, it can be somewhat difficult to discern whether or not an ornament was executed correctly, or at least, where the mistake was. In the absence of an experienced instructor to provide immediate criticism in such instances, the student's inability to evaluate their own technique accurately can lead to wasted practice time and the introduction of bad habits.

This provides the motivation for an algorithm for automatic recognition and evaluation of GHB ornamentation. Such a system would allow the player to gauge their progress and to correct errors quickly, in order to maximise the efficiency of time spent practicing between lessons.

4.2 Related Work

Detection of musical ornamentation in genres other than Highland piping has been addressed in several recent studies. Brown and Smaragdis (2004) use independent component analysis to examine trills in piano and flute recordings, in order to compare trill rates between performances. Gómez et al. (2011) present a method based on the Smith-Waterman algorithm to identify a range of predefined ornamentation techniques in *a cappella* flamenco pieces.

The system described in (Gainza & Coyle, 2007) concerns the detection of ornamentation in Irish folk music. This approach uses onset detection, audio segmentation and pitch recognition functions to find instances of single and multi-note ornaments. Evaluation is conducted on excerpts from tin whistle, flute and pipe recordings, in which a total of 122 single and 27 multi-note ornaments were annotated by the authors.

4.3 Initial Rule-Based Approach ($\mathbf{OR_{2012}}$)

4.3.1 Implementation

The formalised nature of Highland piping ornamentation makes it an ideal candidate area for automatic detection. This section describes the implementation of the first ornament recognition algorithm developed during this project (D. W. H. Menzies & McPherson, 2012), referred to hereafter as OR_{2012}. In order to identify specific embellishments, the OR_{2012} approach makes the following assumptions:

1. An ornament is a series of one or more *gracenotes* in a defined sequence.
2. A gracenote is a note whose duration is less than or equal to a specified limit L. In (D. W. H. Menzies & McPherson, 2012), an experimentally determined value of $L = 85$ms is used.
3. Each ornament has its own particular subset of possible previous and following notes. For example, a *throw on D* can come from any note except Low G, but must end on D.

Based on these principles, a collection of templates corresponding to the common embellishments was produced. The original implementation contained templates for 54 ornaments (or variations of the same ornament). A complete list of the ornaments detectable by the system is provided in Appendix A. From the incoming note data, the algorithm assumes any consecutive string of gracenotes to be a potential embellishment. Upon completion of the sequence (i.e. when a note longer than L is detected) the recognition method is called.

Figure 4.1 shows a flow chart of the OR_{2012} ornament recognition algorithm. Firstly, the notes immediately before and after the detected sequence are considered. Any template for which either of these notes is disallowed is removed from the comparison database. The potential ornament is then compared to the remaining templates in turn, and assigned a similarity rating in each case based on the number of pitches in the performed sequence matching those of the template. In instances where no exact match is found between detected gracenote sequence and ornament template, the system attempts to recognise the performed movement by considering three possible classes of error: *substitutions*, *insertions* and *omissions* (Figure 4.2).

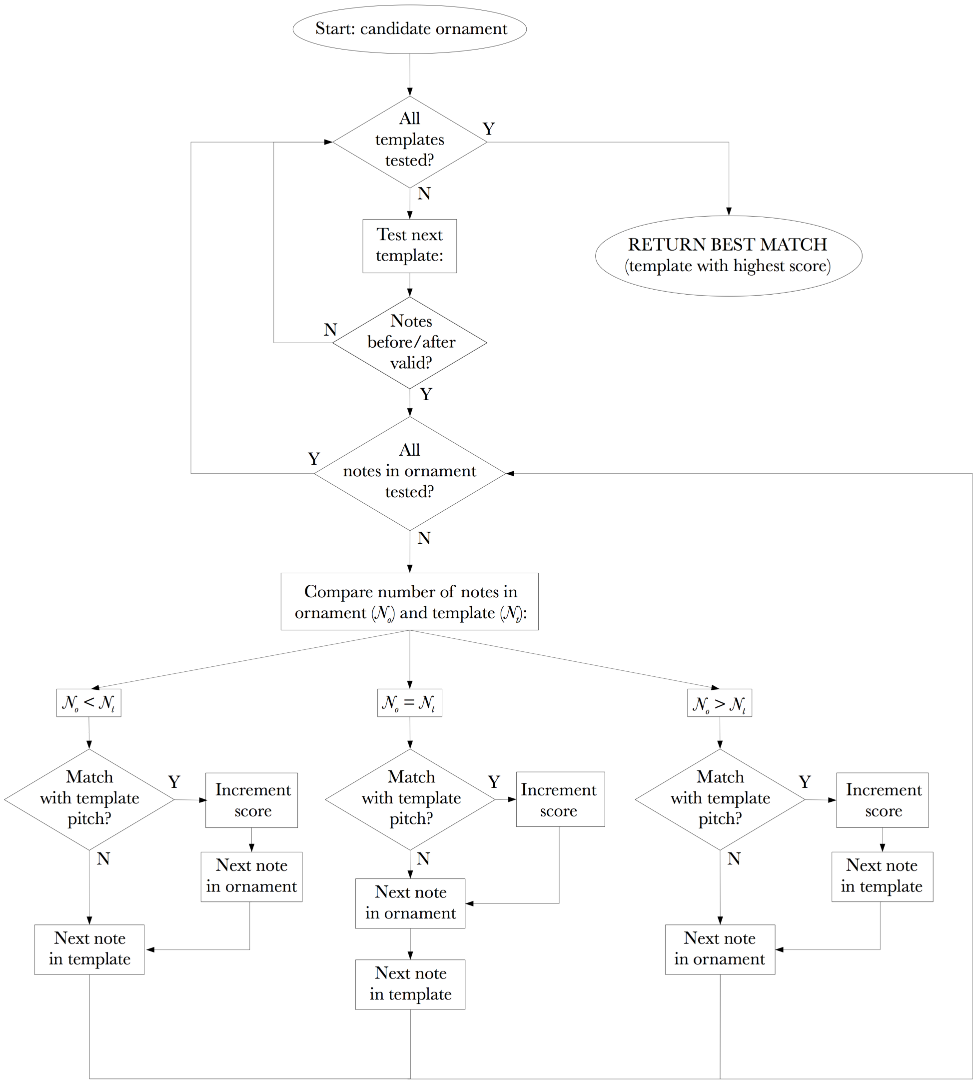
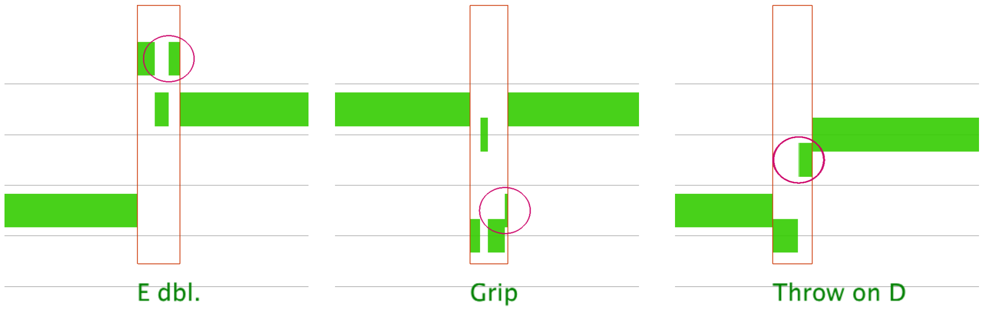


Figure 4.1: Flow chart of OR_{2012} ornament recognition algorithm.

4.3.2 Substitution Errors

The abundance of different embellishments in traditional piping can lead to one or more gracenotes in a sequence being remembered wrongly. If the movement is otherwise correctly executed, the performed ornament will have an equal number of notes to the required template. In this case, the similarity rating between ornament and template is simply assigned according to the number of note indices at which the corresponding pitches match.



(a) (b) (c)

Figure 4.2: Example of ornamentation errors: (a) *E doubling* with substitution error (High G gracenote instead of F gracenote), (b) *grip* with insertion error, (c) *throw on D* with omission error (D gracenote missing between Low G and C).

4.3.3 Insertion Errors

Perhaps the most common type of error in ornamentation, particularly among inexperienced pipers, is the insertion of unwanted additional notes caused by careless transitions between fingerings. The inclusion of such errors within a gracenote sequence will result in the detected embellishment having more notes than the correct template. In such cases, the algorithm compares corresponding note indices until a discrepancy is reached (i.e. a gracenote in the performed embellishment is missing from the template). The pitch and position of the extraneous note are recorded, and the comparison continues from the subsequent point in the detected sequence.

4.3.4 Omission Errors

Another recurring problem among novice players occurs when the player fails to move their fingers with sufficient speed and precision to articulate each note in the movement clearly. This results in the omission of one or more gracenotes, and hence corresponds to the detected ornament being shorter in length than the appropriate template. In this situation, the comparison process is complementary to that of 4.3.3, with any template pitch not present in the performed sequence being deemed an omission error.

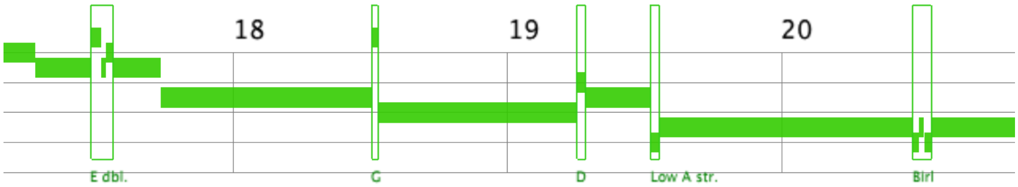


Figure 4.3: Correctly detected ornaments using OR_{2012} detection algorithm.

4.3.5 Limitations of OR_{2012} Approach

Figure 4.3 depicts an excerpt from a performance of the $\frac{4}{4}$ march "The Rowan Tree", recorded using the digital chanter interface. The horizontal green boxes denote ornaments which have been correctly identified using the OR_{2012} algorithm. This approach provides good results for embellishments which are separated by long melody notes, and represents an encouraging proof of concept for the notion of automatic ornament recognition.

However, preliminary testing of the OR_{2012} algorithm revealed two major limitations. The first concerns the initial gracenote sequence detection step. While the constituent gracenotes of most correctly-executed ornaments are generally quite short in duration ($\simeq$ 50ms), it is not uncommon for the first note of certain embellishments (in particular the *throw on D*) to be significantly prolonged to accent the strong beat of a bar. In such instances, the longer note will not be included in the detected gracenote sequence.

Conversely, in faster and more complicated pipe tunes, it is often the case that some melody notes are of comparable duration to gracenotes, and will hence be added to the sequence used for ornament recognition. While the OR_{2012} algorithm does take into account the possibility of errant gracenotes in performed embellishments (as described in Section 4.3.3), the inclusion of too many melody notes in the detected gracenote sequence will inevitably cause recognition errors. These shortcomings influenced the development of an improved ornament detection algorithm, which is described in the following section.

4.4 Dynamic Time Warping (DTW) Approach

The purpose of the ornament detection and evaluation algorithm is to allow the pupil to ensure they are practicing each movement correctly, thus reducing the risk of introducing bad habits in the absence of an experienced tutor to provide immediate criticism. This requires that the system be able to identify poorly executed embellishments reliably, in order to offer constructive feedback to the player. To achieve this, the rule-based approach described in Section 4.3 was extended to an iterative pattern matching algorithm using Dynamic Time Warping (DTW).

DTW is a popular technique for musical pattern recognition. In (Stammen & Pennycook, 1993), DTW is employed to recognise melodic fragments in MIDI keyboard performances of a range of pieces from Bach fugues to bebop. Paulus and Klapuri (2002) use DTW to assess the similarity between temporal rhythmic patterns extracted directly from audio signals. The system presented in (Pikrakis, Theodoridis, & Kamarotos, 2003) applies a DTW-based method to the task of classifying monophonic Greek traditional clarinet recordings according to 12 pre-defined reference patterns.

This section presents the implementation of the DTW-based ornament recognition algorithm, which is referred to as OR_{dtw}. The software includes an XML file containing 64 ornament templates, detailing the pitches and approximate durations of each gracenote in the movement, and all permitted previous and subsequent notes (e.g. a *birl* must always end on Low A).

4.4.1 Improved Gracenote Sequence Detection

The first step in the process is to identify any series of one or more gracenotes as a potential ornament. A gracenote is defined here as any note whose duration falls between two specified lengths L_{min} and L_{max}. However, as discussed in Section 4.3.5, it is often the case that the performer will choose to elongate the first note of certain ornaments for emphasis. For this reason, the OR_{dtw} algorithm begins detecting a possible ornament when any note shorter than a higher limit $L_{poss} > L_{max}$ is reached. If the subsequent note is within the limits defining a normal gracenote, the longer first note is included in the sequence. This ensures that ornaments with extended opening gracenotes, such as the *throw on D* shown in Figure 4.4, can be correctly detected. Once a complete gracenote sequence is detected, it is marked as a potential ornament and compared to each of the templates.

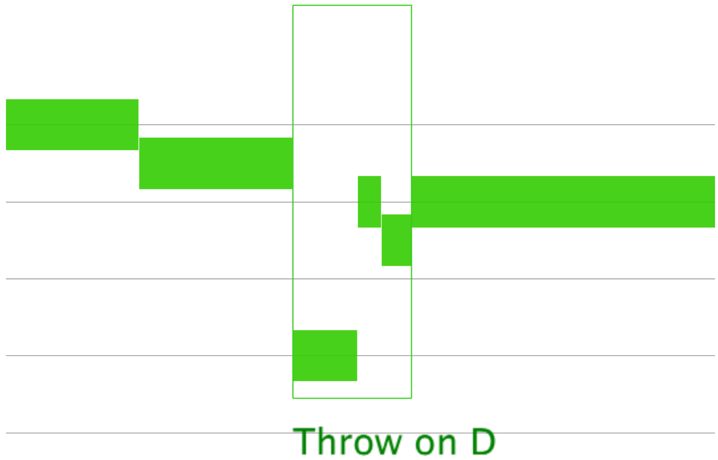


Figure 4.4: *Throw on D* ornament with extended Low G.

4.4.2 Improved Ornament Recognition Using DTW

Figure 4.5 depicts a flow chart of the OR_{dtw} ornament recognition process. Firstly, the complete gracenote sequence is considered. If both the melody notes immediately before and after the potential ornament are valid, then the algorithm attempts to match the gracenote pitches to those in the template.

To compare a detected gracenote sequence o_d of length n frames with an ornament template o_t of length m frames, a DTW algorithm based on the method used in (Turetsky & Ellis, 2003) is employed. The algorithm seeks an optimal path through a *cost matrix* of dimensions $n \times m$, which represents all possible time alignments of the two sequences (Rabiner & Juang, 1993). The cost of the optimal path provides a measure of the similarity between o_d and o_t; the higher the cost, the poorer the match between the two ornaments. This is assigned on a frame-by-frame basis; the cost between template and detected frames with identical pitches is zero, while frames with different pitches incur a cost of one, regardless of the musical interval between them. In practical terms, notes in the detected sequence that are either surplus to or missing from the template incur a cost of one point for each millisecond sample that cannot be matched.

Should the DTW comparison return a cost of zero, this ornament is designated a perfect match and the detection is complete. If the cost is non-zero, or the previous and/or subsequent notes are invalid, the algorithm follows an iterative process, in which three alternative solutions are tested by dropping a gracenote

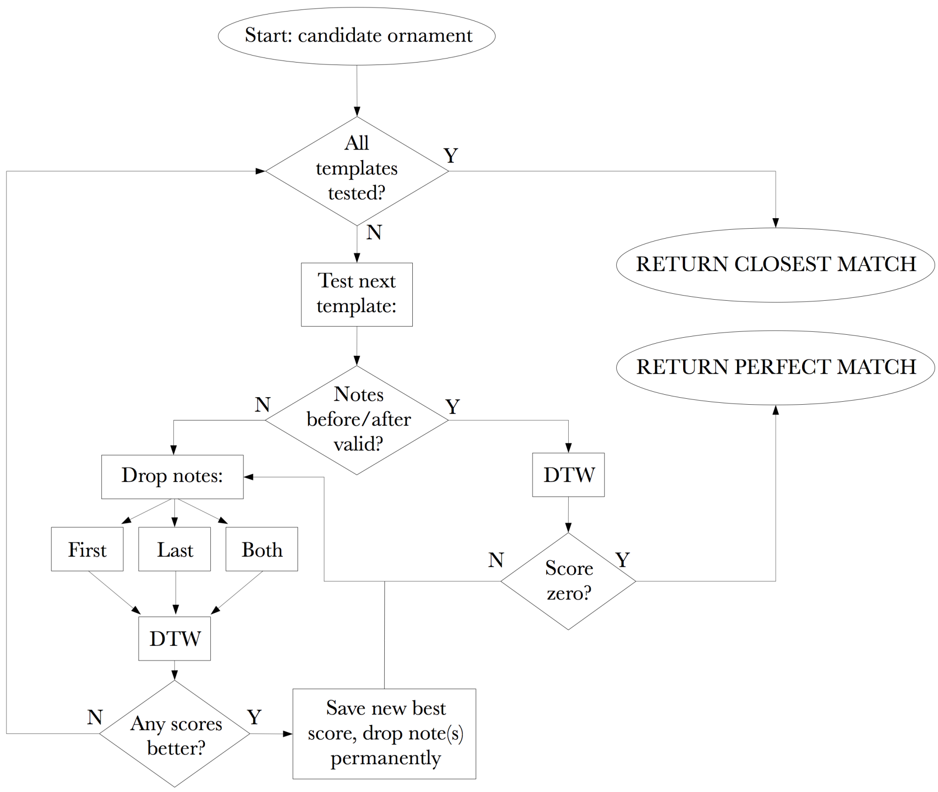


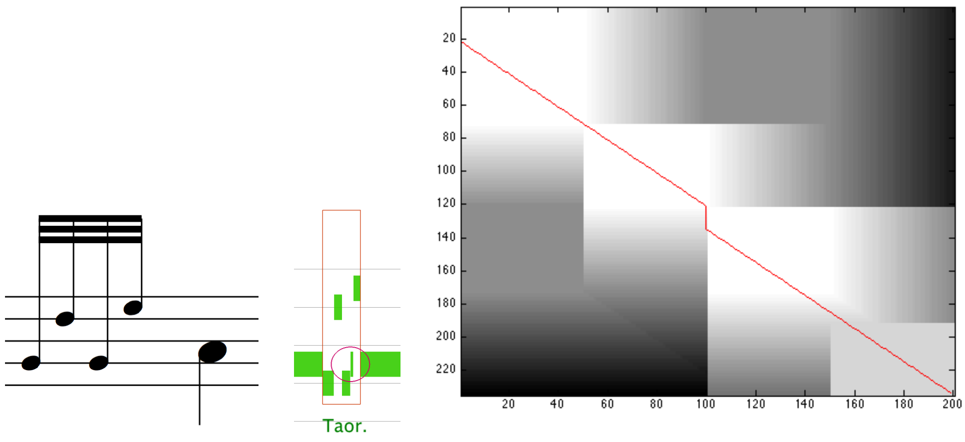
Figure 4.5: Flow chart of OR$_{dtw}$ ornament recognition algorithm.

from (a) the beginning of the sequence, (b) the end, and (c) both. If any of these alternatives provides a better score then this gracenote is dropped permanently (adding a fixed penalty to the score) and the algorithm continues to iterate until no improvement is found, before repeating for the next template.

The OR$_{dtw}$ algorithm allows embellishments performed with significant deviations in both pitch and timing to be identified correctly, thus enabling the system to highlight details of poorly executed ornaments. Figure 4.6 shows a *taorluath* movement which contains an insertion error (circled in red), and the resulting DTW plot showing the cost matrix and optimal path.

4.4.3 Comparison with Previous Approach

The process of iteratively removing notes from the gracenote sequence enables the OR$_{dtw}$ algorithm to identify ornaments within a passage of short melody notes, addressing one of the major limitations of the previous approach (as described in Section 4.3.5). This benefit is illustrated in Figure 4.7, which shows



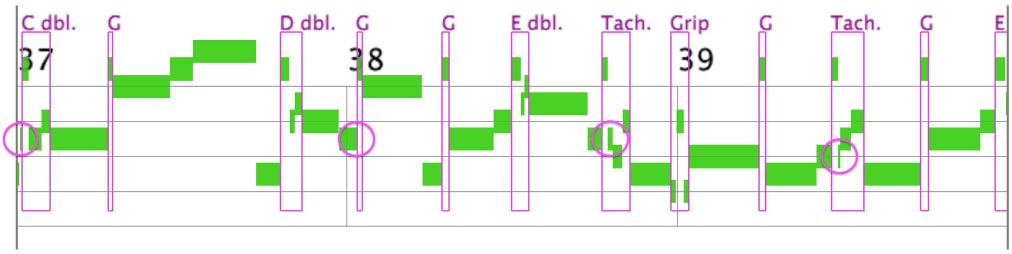
(a) (b) (c)

Figure 4.6: (a) *Taorluath* ornament notation, (b) detected *taorluath* with insertion error, (c) DTW plot.

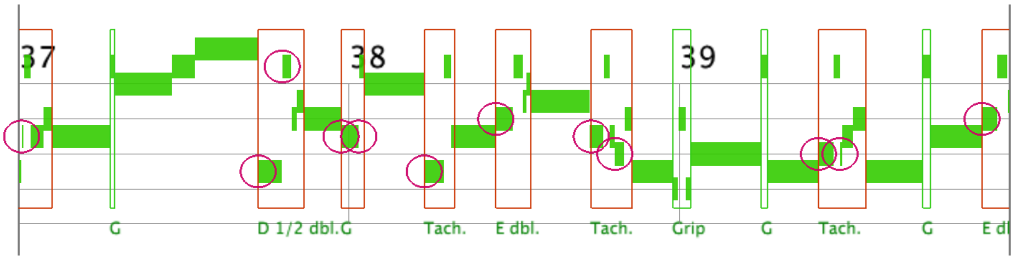
the same excerpt from a performance of the $\frac{2}{4}$ march "Donald MacLean's Farewell to Oban" with three different sets of ornament annotations. The purple rectangles in Figure 4.7(a) represent the ground truth ornaments, which were annotated manually by the author (including the insertion errors identified by purple circles). The ornament annotations shown in Figures 4.7(b) and 4.7(c) were detected using the OR_{2012} and OR_{dtw} algorithms respectively.

It is evident from Figure 4.7(b) that the presence of short melody notes has a negative impact on the performance of OR_{2012}. Two ornaments in the excerpt are incorrectly identified: the *D doubling* in bar 37, and the second G gracenote in bar 38. Furthermore, while the other embellishments in the passage have been correctly recognised, many (such as the *E doubling* in bar 38) have been falsely labelled as containing erroneous gracenotes when these are in fact melody notes. This causes the ornament boundaries to be drawn incorrectly, and leads to a profusion of red circles to highlight the supposed errors.

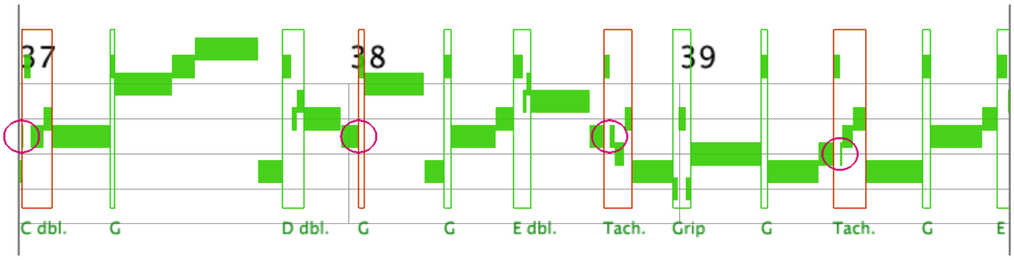
In contrast, the OR_{dtw} algorithm (Figure 4.7(c)) is successful in detecting both the correct identity of all ornaments in the excerpt, and also those which do genuinely contain insertion errors. (It can be noted at this point that the insertion error at the start of bar 38 is so short in duration that it would almost certainly be inaudible. This does raise the question of when an error should be deemed serious enough to be displayed to the user; however this is primarily an interface design issue and does not represent a failing of the ornament detection algorithm



(a)



(b)



(c)

Figure 4.7: Excerpt from "Donald MacLean's Farewell to Oban" showing (a) ground truth ornament annotations with manually annotated insertion errors (circled), (b) ornaments detected using OR_{2012}, (c) ornaments detected using OR_{dtw}. Red circles indicate ornamentation errors detected in each case.

in itself.)

4.5 Evaluation

This section describes a quantitative evaluation of the performance of the DTW ornament detection algorithm (OR_{dtw}), alongside the original approach described in Section 4.3 (OR_{2012}). The algorithms were tested on a dataset of 30 performances recorded using the digital chanter interface: a first set comprised of 5 performances each by 3 professional bagpipers, and a second group of 15 recordings made by 11 piping students (1 or 2 pieces by each player). The students were aged 11-17 years, and had been learning the bagpipes for 1-4 years.

The two recognition algorithms were tested using identical settings for gracenote sequence detection: $L_{min} = 15$ms, $L_{max} = 100$ms and $L_{poss} = 170$ms. These values were determined empirically during the development of the system, and were not altered at any point during the evaluation. The complete ornament template table of 64 templates (Appendix A) was used for both algorithms.

4.5.1 Annotation of Ground Truth Ornaments

Prior to the evaluation, the recordings were manually annotated to provide a ground truth reference for the type and location of each of the embellishments attempted by the player. In some cases, the incorrect execution of one ornament can manifest itself as a slightly distorted instance of a different technique. The aim of the algorithm is to identify ornaments, however poorly executed, without any prior knowledge of the performer's intention. For this reason, the criterion for annotation of the ground truth ornaments was whether or not an experienced human listener would be able to determine from the context which ornament was attempted, without necessarily knowing the correct ornamentation of the tune. Over all 30 performances, a total of 3629 ground truth ornament annotations were made.

4.5.2 Results

For each algorithm, the detected embellishments were compared to the ground truth annotations, giving a number N_C of correct matches in each case. The algorithms were evaluated for *precision* P and *recall* R, which are given by:

$$P = \frac{N_C}{N_D} \quad \text{and} \quad R = \frac{N_C}{N_A}$$

where N_D is the total number of ornaments detected, and N_A is the number of ground truth annotations. The P and R values can then be combined into a single *F-measure* statistic by which to compare the algorithms:

$$F = 2\left(\frac{PR}{P+R}\right)$$

The P, R and F values obtained by the two algorithms are presented in Table 4.1. Across all 30 test recordings, the OR_{dtw} algorithm achieved an F-measure of 0.923, an increase of 0.068 (6.8%) over the OR_{2012} result. The improvement in performance is greatest for the "Experts" recordings, where OR_{dtw} attained 0.9649 (7.8% higher than OR_{2012}), while in the "Students" category the accuracy increased from 0.816 to 0.8652 (4.9%). To provide a measure of the statistical significance of the F-measures in Table 4.1, paired-sample t-tests were computed using the OR_{dtw} and OR_{2012} results for each recording (Table 4.2). In all categories, the improvement in performance was found to reject the null hypothesis at a significance level of 99.9% ($p < 0.001$).

Group	Recordings	Algorithm	N_A	N_D	N_C	P	R	F
Experts	Expert 1 (5 pieces)	OR_{dtw}	1377	1348	1326	0.984	0.963	0.973
		OR_{2012}		1349	1191	0.883	0.8649	0.8738
	Expert 2 (5 pieces)	OR_{dtw}	524	504	498	0.988	0.950	0.969
		OR_{2012}		501	477	0.952	0.910	0.931
	Expert 3 (5 pieces)	OR_{dtw}	439	422	402	0.953	0.916	0.934
		OR_{2012}		426	379	0.900	0.863	0.876
	All	OR_{dtw}	**2340**	**2274**	**2226**	**0.979**	**0.951**	**0.9649**
		OR_{2012}		**2276**	**2047**	**0.899**	**0.8748**	**0.887**
Students	Highest (1 piece)	OR_{dtw}	62	62	60	0.968	0.968	0.968
		OR_{2012}		59	58	0.983	0.935	0.959
	Lowest (1 piece)	OR_{dtw}	88	88	56	0.636	0.636	0.636
		OR_{2012}		96	53	0.552	0.602	0.576
	All	OR_{dtw}	**1289**	**1240**	**1094**	**0.882**	**0.849**	**0.8652**
		OR_{2012}		**1296**	**1055**	**0.814**	**0.818**	**0.816**
Both	**All**	OR_{dtw}	**3629**	**3514**	**3320**	**0.9448**	**0.9149**	**0.930**
		OR_{2012}		**3572**	**3102**	**0.868**	**0.8548**	**0.862**

Table 4.1: Comparison of ornament detection algorithms across all pieces in expert and student groups. The "Highest" and "Lowest" labels refer to the individual student performances which produced the best and worst ornament detection results respectively.

Group	Num Pieces	t-value	p-value
Experts	15	4.5614*	4.4394^{-4}
Students	15	4.3431*	6.7492^{-4}
All	30	6.3840*	5.5854^{-7}

Table 4.2: Paired-sample t-tests for performance of OR_{dtw} and OR_{2012} ornament detection algorithms (*$p < 0.001$).

4.5.3 Discussion

For the OR_{dtw} algorithm to be valuable to students, it must provide an accurate account of which ornaments were performed, and which contained mistakes. Of the 1240 ornaments detected in the student recordings, 249 (20%) were found to contain errors. 209 (84%) of these 249 ornaments were correctly matched to the ground truths. This is an encouraging result; however, there are still instances in which the player's technique leads to incorrect recognition.

Ornament recognition errors generally occur for one of two reasons. The first is that poor execution can result in the detected sequence more closely resembling a different ornament. For this reason, the process of annotating ground truth ornaments involved some ambiguity, particularly for the student performances. The annotations were made based on the contextual knowledge an expert piper would use to discern the player's intention. This high-level understanding of the wider context of the piece is not implemented in the detection algorithm itself.

The second cause of mis-identification takes place in the gracenote sequence detection step, when the duration of one or more notes in a performed embellishment falls out-with the pre-defined bounds. In this case, single note ornaments are ignored entirely, and multi-note ornaments are often identified as some combination of their constituent gracenotes. This situation is particularly common among beginning players. Indeed, it is generally considered preferable for early stage pipers to practice embellishments slowly and clearly at first, rather than attempting to execute the movement at full speed and developing bad habits (Shepherd, R.T., 2002). It is therefore clearly desirable that the algorithm be able to detect ornaments performed in this way. In the following section, the parameters of the gracenote sequence detection step are adjusted in order to determine the optimal settings for ornament recognition accuracy.

4.6 Tuning Parameters for Gracenote Sequence Detection

The results presented in Section 4.5 were obtained using the values $L_{min} = 15$ms, $L_{max} = 100$ms and $L_{poss} = 170$ms for gracenote sequence detection. These were determined empirically during the development of the system using performances recorded by the author, and were maintained for the evaluation so as not to bias

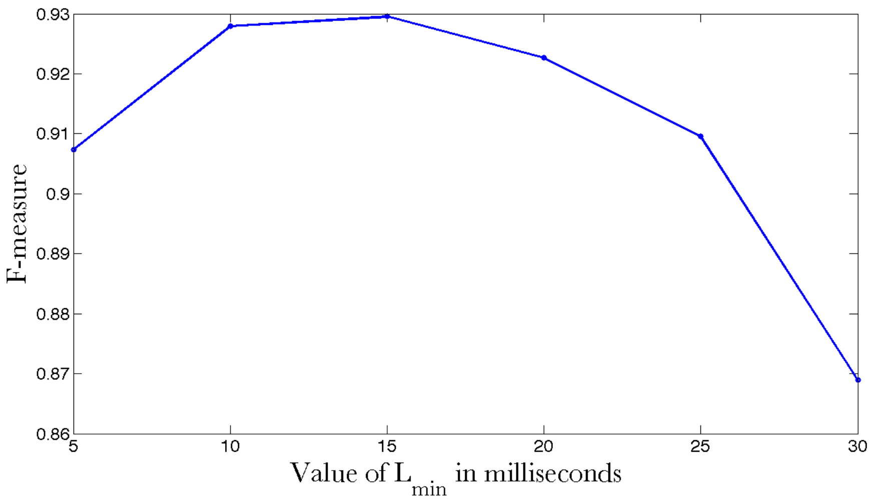


Figure 4.8: Performance of OR_{dtw} algorithm over all 30 test pieces for different values of L_{min}. Other parameters are maintained at default values (L_{max} = 100ms and L_{poss} = 170ms).

the comparison between the OR_{dtw} and OR_{2012} algorithms. Having established the performance of the two approaches using these default settings, the collection of 30 annotated recordings provides an opportunity to investigate how the L_{min}, L_{max} and L_{poss} parameters might be tuned in order to achieve the best results for a much larger and more diverse dataset than was previously available.

4.6.1 Adjusting L_{min} Parameter

The L_{min} parameter defines the lower limit for duration of detected gracenotes, and is used to prevent very short transitionary states between notes being recognised as ornaments. To assess the effect of changing this threshold, the performance of the OR_{dtw} across all 30 pieces was tested repeatedly while the value of L_{min} was adjusted in 5ms increments. The L_{max} and L_{poss} parameters were maintained at the default settings (L_{max} = 100ms and L_{poss} = 170ms). The resulting F-measures for each value of L_{min} are shown in Figure 4.8. From this plot it can be seen that the default setting of L_{min} = 15ms provides the best performance (F = 0.930), and hence this value remains unchanged hereafter.

4.6.2 Adjusting L_{max} Parameter

As discussed in Section 4.5.3, one of the most common causes of ornament recognition errors in the evaluation is the misidentification of gracenotes which are too long to be detected. For this reason, it may be beneficial to increase the L_{max} parameter, such that embellishments performed slowly (e.g. by a student taking care to execute each movement accurately) can be correctly recognised. In practice, this seems likely to be a trade-off with the performance of the algorithm for faster tunes (e.g. some of the pieces in the "Experts" category), as increasing the threshold too far would lead to a large number of melody notes being included in the gracenote sequences used for ornament recognition.

Figure 4.9 shows the F-measures obtained across all 30 test recordings when L_{max} is adjusted in increments of 10ms. The L_{min} and L_{poss} parameters are maintained at their default settings for all L_{max} values up to 170ms, whereupon L_{poss} is set to $L_{max}+1$ms to ensure correct operation of the algorithm. It is clear from the plot that the performance of the algorithm improves steadily as L_{max} is increased, until reaching a peak of $F = 0.951$ at $L_{max} = 160$ms. A paired-sample t-test comparing the results for $L_{max} = 160$ms with those obtained using the default settings suggests that this improvement is statistically significant ($p < 0.05$).

As expected, this effect is most prominent in the "Students" category, for which the F-measure increases from 0.865 to 0.923, a significant improvement in ornament recognition accuracy ($p < 0.01$). The "Experts" recordings are largely unaffected by the change in L_{max}, improving very slightly from $F = 0.965$ to $F = 0.966$, though this was found not to be statistically significant ($p > 0.05$). This shows that the L_{max} parameter can be increased considerably, allowing longer gracenotes played by beginning students to be detected, without incurring a negative effect on the performance of the OR_{dtw} algorithm for faster pieces.

4.6.3 Adjusting L_{poss} Parameter

Figure 4.9 shows the effect of adjusting the L_{poss} parameter when L_{min} is kept at the original default value of 15ms, and L_{max} is set to new optimal value of 160ms. It can be seen that L_{poss} has very little effect on the performance of the algorithm with the newly extended L_{max}. An extremely modest improvement from $F = 0.920$ to $F = 0.923$ for the "Students" recordings is obtained by

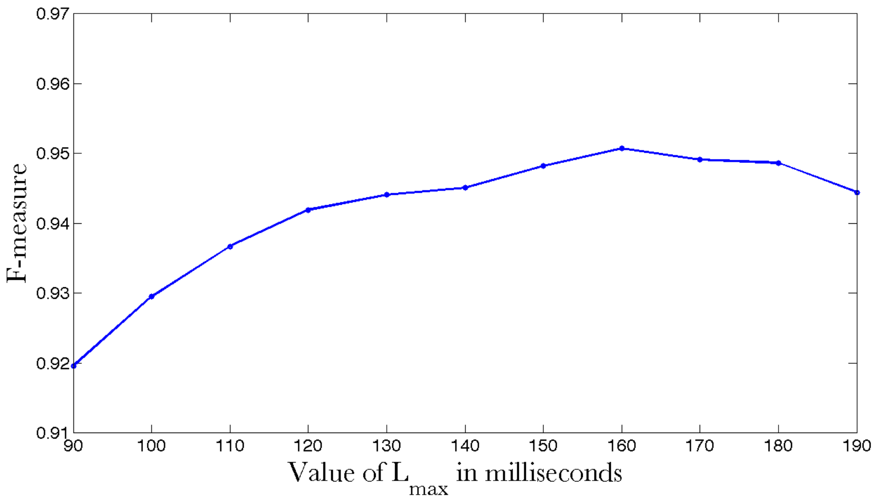


Figure 4.9: Performance of OR$_{dtw}$ algorithm over all 30 test pieces for different values of L_{max}. Other parameters are maintained at default values (L_{min} = 15ms and L_{poss} = 170ms), except for $L_{max} \geq 170$, in which case $L_{poss} = L_{max} + 1$ms.

increasing L_{poss} from 161ms (L_{max} + 1) to 180ms, which corresponds to an additional 4 ornaments being correctly detected out of the 1289 ground truth annotations in this category; this was not found to be statistically significant ($p > 0.05$).

4.6.4 Discussion of Optimal Parameter Settings

The optimal value for the L_{max} parameter determined in Section 4.6.2 provides greatly improved ornament recognition accuracy for student recordings in which gracenotes can be longer than expected, without having a detrimental effect on the performance of the OR_{dtw} algorithm for more intricate tunes. This is a particularly important result, as assisting early stage players was the primary motivation for the development of the algorithm. Moreover, it is important that the system should not be seen to contradict the advice of a human instructor to practice each embellishment slowly at first, prioritising accuracy over speed, and hence the ability to detect ornaments performed in this way is of great benefit.

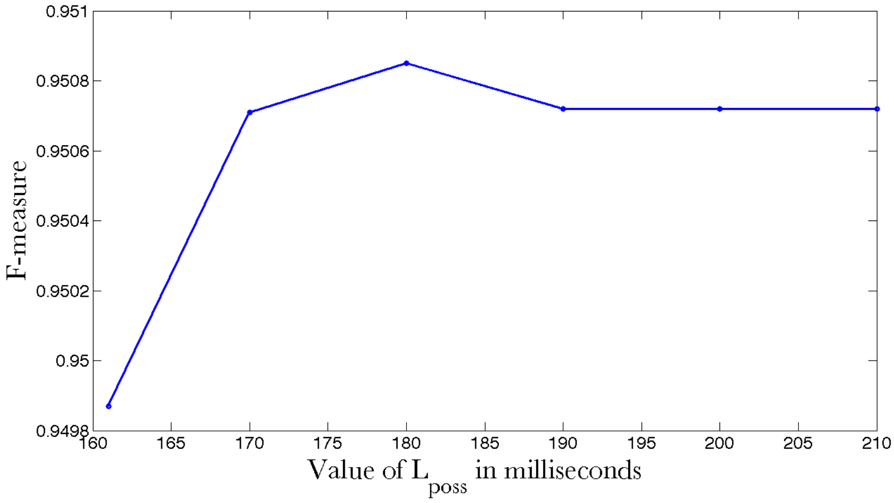


Figure 4.10: Performance of OR_{dtw} algorithm over all 30 test pieces for different values of L_{poss}. The L_{min} parameter is maintained at the original default value of 15ms, while L_{max} is set to 160ms (the optimal value determined in Section 4.6.2).

4.7 Application to Automatic Transcription

While the primary purpose of the ornament recognition algorithm is to be included as part of an assistive software package for tuition and solo practice, the capability to identify ornaments in a recorded performance provides other potential benefits to the piping community. This section briefly describes the application of the algorithm to automatic transcription of Highland bagpipe notation.

The process of manually transcribing GHB music, either by hand or with notation software such as Sibelius or Finale, can be a lengthy one. In particular, digital typesetting of the many embellishments is especially tiresome. This issue has been addressed by the *PiobMaster* notation program[1], which features drop-down menus for a wide range of Highland piping ornaments to accelerate this otherwise time-consuming process.

However, while many notation packages support automatic transcription from user input (generally using a MIDI keyboard), PiobMaster does not provide this facility. Since several commercially available digital bagpipe chanters are MIDI compatible, it is likely that the lack of an automatic transcription function is due to the inability of existing software to distinguish Highland piping embel-

[1] `http://www.ceolmor-software.com/piobmasterpro.html`

lishments from melody notes.

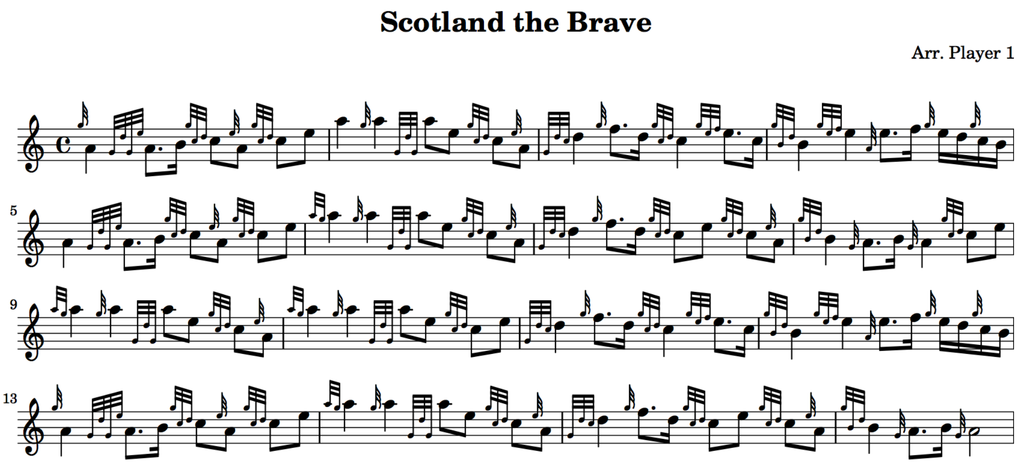
The OR_{dtw} algorithm solves this problem, allowing performances recorded using the digital chanter interface to be transcribed automatically. This simply requires the player to input the time signature of the piece, then record along to a metronome at the desired tempo. Once the performance is complete and the OR_{dtw} algorithm has detected the ornaments, the transcription algorithm operates as follows:

1. Firstly, the performance is separated into bars based on the tempo and time signature entered by the user.
2. Since embellishments are not prescribed any duration in the notation of bagpipe music (as is also the case with ornaments such as *acciaccatura* or *appoggiatura* in Western classical music), the durations of all detected ornaments are distributed between the previous and subsequent melody notes.
3. For each bar, the melody notes (including durations added from detected embellishments) are quantised to a grid defined by the shortest metric unit in the tune (e.g. semi-quavers).

The resulting sequence of detected ornaments and quantised melody notes in each bar is then converted into a musical score by producing a script in the *Lilypond* open source music engraving format[2]. Figure 4.11(a) shows the score for $\frac{4}{4}$ march "Scotland the Brave", generated automatically from a performance by a professional bagpiper using the digital chanter interface. The existing sheet music used for the performance is shown in Figure 4.11(c). Comparison of the two scores shows that all ornaments in the piece were correctly detected. The only errors in the transcription occur at the dotted semi-quaver passages in bars 4 and 12, since the quantisation algorithm does not currently support note durations below one semiquaver.

Automatic music transcription is an active field of research (Benetos, Dixon, Giannoulis, Kirchhoff, & Klapuri, 2013), and is largely beyond the scope of this thesis; the method described above is merely an illustration of the potential of the ornament detection algorithm for applications other than those immediately addressed in this work. In order to refine this approach for practical use, two primary areas for development (in addition to the obvious inclusion of a user interface for editing recorded performances) should be considered.

[2] `http://lilypond.org`



(a)

(c)

Figure 4.11: (a) Notation for "Scotland the Brave" generated automatically from recorded performance, (b) original score used for performance.

Firstly, the grid-based quantisation employed here necessitates a somewhat mechanical adherence to the metronome to avoid transcription errors. This is not entirely inappropriate for an application where the player would be deliberately aiming to make their performance as intelligible as possible to the system, as would generally be the case when using such a program as an alternative to manual transcription of a tune. However, it is nonetheless likely that by employing a more flexible quantisation framework to allow some expressive deviations in timing, such as that described in (Cemgil, Desain, & Kappen, 2000), the user experience would be improved.

Secondly, when distributing the duration of the detected ornaments between the surrounding melody notes, the current approach simply allocates the previous and subsequent notes half each of the total ornament length, regardless of the type of embellishment. In reality, where an ornament falls with regard to the beat is rather a subtle point, dependent on both the type of ornament and the player's own expressive preference. Since some embellishments last for several hundred milliseconds, a more sophisticated method for determining which melody note should be assigned the duration of a given ornament would almost certainly be a valuable improvement.

4.8 Summary

This chapter has described the motivation for, and implementation of an algorithm for the automatic recognition and evaluation of Highland piping embellishments performed using the digital chanter interface. An extensive evaluation comparing two approaches is presented, and optimal parameter settings determined which provide accurate recognition of ornaments played by both student and expert pipers. Lastly, the potential of the algorithm for automatic transcription of Highland bagpipe notation is demonstrated. In the following chapter, this algorithm is incorporated into a complete GUI software system to support the learning process for piping students in both one-to-one tuition and solo practice situations.

Chapter 5

Highland Piping Tuition Software System

This chapter describes the development of a graphical user interface (GUI) application to assist in Highland piping tuition and solo practice. The program uses sensor input from the digital chanter presented in Chapter 3, and incorporates the ornament recognition algorithm developed in Chapter 4, bringing these threads of research together to form a complete hardware and software system to support the GHB learning process.

In Section 5.1, the requirements for such a system (in terms of user features) are discussed. Section 5.2 provides a brief outline of an early prototype of the program. This prototype was used in a preliminary user study with an experienced piping instructor and seven students, in order to gauge initial reactions and gather feedback to inform the continued development of the software. The procedure and outcomes of this pilot study are described in Section 5.3.

The final GUI system includes controls for recording, playback and visualisation of performances with the aim of assisting an instructor in describing their feedback on a student's playing. Section 5.4 provides a detailed description of the operation and implementation of these features. Additional developments for automatic identification of errors in ornamentation and fingering are discussed in Section 5.5. An alternative version of the GUI incorporates the recording and performance analysis functions into a game environment designed to encourage motivation to practice among younger learners. This program, known as *Bagpipe Hero*, is described in Section 5.6.

5.1 Motivation and Requirements

5.1.1 Recording and Playback

Recording performances and practice sessions for the purposes of critical listening and evaluation has considerable merits when learning a musical instrument (Klickstein, 2009). Perhaps the most fundamental benefit of the digital chanter interface over a traditional acoustic chanter is that it enables detailed measurements of the player's finger movements to be captured with a high degree of temporal resolution. Performances can then be stored as a collection of time-stamped frames of sensor values, which presents several advantages over a simple audio recording.

Firstly, this symbolic representation provides a great deal of flexibility in terms of audio playback: performances can be reproduced at different speeds; a metronome track can be easily added or removed; multiple recordings of the same piece can be played together or individually; and navigation to a particular point in the performance can be made very straightforward with appropriate GUI features. Moreover, saving the raw sensor data facilitates various forms of automatic analysis of the player's technique that would be difficult or impossible from an audio signal alone.

5.1.2 Visualisation

In addition to incorporating controls for recording and playback, the inclusion of a GUI provides an opportunity for a further mode of analysis through visualisation of recorded performances. As discussed in Section 1.2.3, expressive rhythmic phrasing is a subtle yet critical aspect of Highland bagpipe performance, and one which can be challenging for piping tutors to explain to their students. A visual display providing a meaningful representation of the variations in timing between performances could therefore be a useful tool to assist an instructor in communicating such feedback.

A visualisation scheme based on transcription of performances into conventional musical notation (such as the method described in Section 4.7) would be inappropriate for this purpose, as this necessarily involves some level of quantisation. For this reason, the GUI system described in this chapter instead uses a proportional representation similar to the familiar *piano roll* format to illustrate note duration (Figure 5.1). This allows the nuances of a player's rhythmic phrasing,

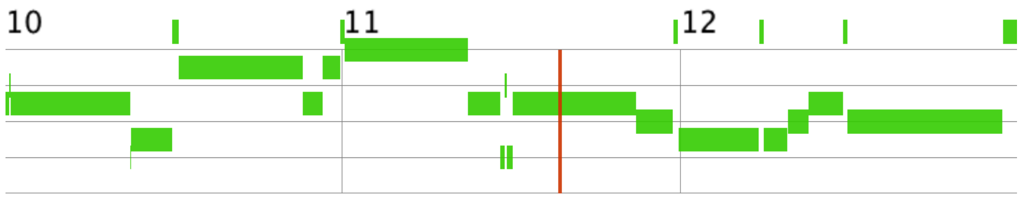


Figure 5.1: Excerpt from recorded performance illustrating proportional rhythmic representation and playhead (red vertical line) showing playback position.

which would be obscured by standard notation, to be clearly and explicitly depicted. Pitches and bar lines are displayed using the traditional staff system (maintaining the piping convention of omitting the accidental symbols on the C♯ and F♯).

5.2 Prototype GUI System

This section provides a brief overview of the initial prototype GUI program (D. W. H. Menzies & McPherson, 2013), developed with the aim of obtaining feedback from a pilot user study, which is discussed in Section 5.3. The implementation of the final system is described in detail in Section 5.4.

The GUI software allows performances to be recorded using the digital chanter interface, and displayed on the screen using the visualisation scheme described in Section 5.1.2 (Figure 5.1). The recording can then be played back, either in its entirety or from anywhere in the piece by clicking on the desired starting location. During playback, a playhead moves across the staff to indicate the current point in the performance.

The prototype system allows only one chanter to be recorded at a time, the idea being that the instructor would record first to demonstrate the piece, following which the student would record along using the tutor's performance as a guide. While recording, the playhead scrolls through the original performance (continuing onto multiple pages if necessary), and the results of the pupil's playing can be shown contemporaneously or hidden as preferred. Once complete, the two performances can be displayed either individually or overlaid in different colours, allowing subtle variations in timing to be identified and examined visually (Figure 5.2). The recordings can also be played back together or separately, and slowed down to 1/2x or 1/4x speed. This enables direct and repeatable compari-

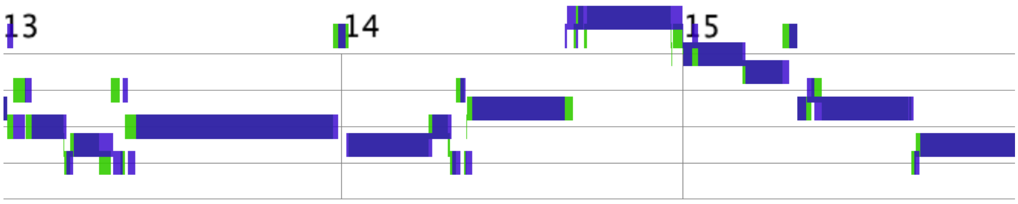


Figure 5.2: Excerpt from two performances of the same piece, overlaid to illustrate subtle variations in timing.

son between performances, promoting critical listening on the part of the student and providing the instructor with an additional tool with which to explain their feedback.

5.3 Pilot Study with Prototype GUI System

5.3.1 Location and Participants

A pilot user study with the prototype system was carried out in March 2013, at a private boarding school in the North East of Scotland. The study took place under the supervision of the school's piping instructor, a highly proficient piper with around thirty years experience of playing and twenty years of teaching, thirteen of which had been spent at the school. At the time of this study, there were forty-seven piping students at the school, aged between eight and eighteen years. Based on his detailed knowledge of the pupils' playing, the instructor selected seven students to participate in the sessions. The participants were aged between thirteen and seventeen years, and their playing experience ranged from six months to eight years.

5.3.2 Procedure

The study took place over a period of four days, the first of which was spent with the instructor only, in order to gather and address his initial comments on the system prior to using it with the pupils. A short interview was also carried out to learn more about his approach to teaching, and some of the particular challenges faced by piping instructors. In response to this discussion, some minor adjustments to the calibration of the tone hole sensors were made in order to ensure that the playing experience was as similar as possible to an acoustic bagpipe chanter.

Each of the students had one session (between 30-60 minutes) with the digital chanter as part of their normal one-to-one lesson time. In each case the student was given some time to get used to the interface. The instructor would then record a tune while the pupil listened, following which the visualisation and playback mechanisms were demonstrated. The student was then instructed to play the same piece. Once the student had finished recording, the instructor would use the visualisation and playback functions to illustrate his observations about the pupil's performance. This process was typically repeated several times per lesson, often with different tunes. Following the sessions, students were given a short survey consisting of seven Likert-type questions and an additional space for further comments. The full questionnaire is provided in Appendix B.

5.3.3 Introductory Interview with Instructor

The introductory interview with the instructor raised several important considerations. Firstly, when asked to describe any differences he had observed when teaching pupils with experience of other musical instruments (as opposed to those who only play the bagpipes), he replied[1]:

> ***Pipe music is so different*** *[...]* ***the way we express our tunes isn't the way it's written.*** *Take 2/4 marches for example; our first beat in the bar is really pushed out to more than we would actually write it, and so we tend to exaggerate by singing it orally and really pushing out these notes. Sometimes when I've had musicians who've played other instruments, they way they would play pipe tunes is totally different to somebody who had just learned pipes from the start.* ***In fact, the guy who was director of music [at the school] two before [the current director], he started learning the bagpipes, and he found it very very hard to get to grips with the phrasing of our tunes, the way we phrase our music*** *[...] and when it came to embellishments, where the embellishments were coming, what bit was coming on the beat, because he was analysing every little movement [...] So to somebody like that, you had to actually explain in depth "that's going to be on the beat" [...] It was quite interesting teaching him, because* ***he had such a wealth of knowledge musically, but when it came to pipe music with all our embellishments and ornamentation he was lost.*** *[For example] if you're playing an E doubling on the beat; he's looking at the E being the beat, as opposed to the G gracenote taking you to the*

[1]Emphasis added by author.

> *E doubling on the beat. So for him it was trying to get his head round "Well that's the beat note there," and I'm saying "No, because that ornamentation takes you into the beat".*

This supports the motivating assumption (Section 5.1.2) that verbal description of the characteristic rhythmic phrasing of Highland bagpipe music can be problematic, even for an expert instructor with a musically accomplished student. Moreover, when asked what he thought were the greatest challenges involved in teaching the bagpipes, the instructor replied that keeping students' levels of interest in the instrument during the early stages of learning can be demanding:

> ***I think it's the timescale that it takes to become a piper.*** *It's not an instant thing; when you start off learning, just even that first couple of weeks, trying to get your fingers in the right position covering the holes to make the first sound, low G - with some kids that can be a couple of weeks [...] and then* ***it's all the scales and embellishments that you have to then learn before you even think about getting onto your first tune.*** *It's the whole buildup process of getting scales and embellishments and a few tunes, and then you've got to go through the whole thing of memorising them [on a practice chanter] before you get to look at bagpipes. So you've got this whole process to go through before you even get to this instrument that you're dying to get onto.* ***So from a teaching point of view, it's about trying to keep that enthusiasm there, and almost dangle that carrot*** *[. . .] you don't want to have them thinking "och, this isna worth it, I'll give up and go and play something else".*

The instructor went on to describe how he has previously employed technology (in the form of the commercially available DegerPipes digital chanter) for the purposes of maintaining enthusiasm among his students. However, he expressed some reservations about extended use of such tools because of the risk that they might encourage the development of certain bad habits in technique:

> *I've got a set of DegerPipes as well that now and again if we're having a wee practice, a wee bit of downtime we'll get the Degers out and plug them into an amp and pass it round the band and everyone's got to play a tune [. . .]* ***Everyone gets a wee buzz out of it. I mean, the only thing you've got to watch with some of these things is that you don't get into any bad habits*** *[. . .] You can play through stuff on the Degers and your fingers can be all over the place but it still sounds great, so from that point of view that would be one thing I'd be wary of [. . .] You can have the bottom hand totally off and the top hand still sounds fantastic [. . .] That's one of the things from the electronics side of things, you want to be able to get them*

> *picking up on bad habits [...] Something that if they false fingered they just got a clout round the lug! [...]* ***If there was any way that it were able to flag up false fingering, like if the note turned red, so that they were aware "I've done something wrong there".***

This highlights not only a serious limitation of current digital chanters, but also an area of piping technique in general for which the GUI program could provide significant benefit, since false fingering can be difficult to discern even on acoustic instruments (particularly practice chanters). For this reason, the final system developed after the pilot study incorporates the facility for automatic detection and description of false fingering errors; this is described in Section 5.5.2.

5.3.4 Instructor Feedback from Pilot Study Sessions

During the lessons, there were several instances in which the instructor identified specific ornaments which regularly caused the student to lose track of the beat as a result of incorrect phrasing. In such cases, it was possible to locate these points using the display and compare the two recordings both visually and aurally, allowing the pupil to analyse their own playing with the instructor's comments (e.g. *"you're labouring the throw on D"*) in mind. At the conclusion of the study, the instructor described the system as *"a great idea"* and *"such an interesting piece of kit"*, saying that he could definitely envisage it being used regularly in his lessons. He felt that the proportional notation provided an intuitive means of visualising rhythmic phrasing, and stated that even he had found it helpful in illustrating exactly how he played certain embellishments relative to the beat. He also recommended that by providing the facility for two people to record simultaneously using separate electronic chanters, a more meaningful illustration of the differences in rhythmic phrasing might be obtained.

Furthermore, the instructor suggested that in addition to being used in lessons, the system could also prove to be a useful tool for solo practice. He reported that he regularly asks his pupils to identify for themselves how their performance could be improved before providing feedback, so as to promote critical listening to their own playing when practicing alone. By using the system to identify problem areas and repeatedly comparing their performance to the instructor's recording, the student could keep track of their progress and avoid introducing bad habits between lessons. Lastly, with regard to the issue of maintaining students' enthusiasm for practice, he described the system as *"a fantastic thing to get people enthused"*.

Likert statement	Mean response
I found the physical feel of the digital chanter was realistic to play.	4.2 / 5
I found the sound quality realistic.	4.0 / 5
I found the system easy to use.	4.4 / 5
I found the display easy to understand.	4.2 / 5
I found the system fun to use.	4.8 / 5
I think the system would be useful as a practice tool.	4.6 / 5
I would use the digital chanter system in my lessons and practice.	4.4 / 5

Table 5.1: Mean student responses to survey questions.

5.3.5 Student Feedback from Pilot Study Sessions

Table 5.1 shows the mean response to each question in the Likert-style questionnaire described in Section 5.3.2, which was completed by five of the seven students. Possible answers ranged from 1 ("strongly disagree") to 5 ("strongly agree"). The numerical results indicate that the system was well received by the pupils. The lowest score was 4.0 for the perceived authenticity of the GHB sound, which may well be improved if the audio were to be reproduced through headphones or a loudspeaker system of reasonable quality rather than the built-in speakers on a laptop. The result of 4.6 in response to the statement *"I think the system would be useful as a practice tool"* is particularly encouraging, and the reaction to *"I found the system fun to use"* (4.8) is aligned with the instructor's assertion that it could help generate and maintain enthusiasm for practicing. The students also suggested several possible improvements to the system, which included a zoom feature to focus on specific sections, and making the operation of the software more intuitive for the user.

5.3.6 Conclusions from Pilot Study

The primary purpose of this pilot study was not to evaluate the overall success of the system, but rather to gather participant reactions to the initial prototype and to generate ideas for further development. To this end, the feedback obtained was both positive and constructive. The instructor felt it had significant potential to be a valuable teaching tool in one-to-one piping lessons, and could also prove useful for solo practice. The study also yielded some promising avenues for further work (e.g. the capacity to highlight false fingering) and some important criticisms regarding the user interface design. These comments informed the development of the final GUI program, which is discussed in the following sections.

5.4 Final GUI System

This section describes the final software system developed during this project. Written in C++ using the JUCE class extension libraries[2], the program includes facilities for recording, playback and visualisation of performances using the digital chanter interface presented in Chapter 3. This extends the ideas explored with the prototype system described in Section 5.2, taking into account participant comments obtained during the pilot study (Section 5.3).

The complete GUI application also incorporates the ornament recognition and evaluation algorithm presented in Chapter 4, and new functionality for the automatic detection of piping-specific fingering errors. This allows feedback on the player's technique to be generated. These error detection facilities are described in Section 5.5.

The system is controlled by the user from a single GUI window. This is shown in Figure 5.3, with coloured annotations identifying the different sections of the interface. For each of these regions of the GUI, the corresponding features and their implementation are described in detail below.

5.4.1 Opening and Saving Sessions

5.4.1.1 User Controls

Each time the program is launched, a "session" is opened. Depending on the user's preference, a session could correspond to all lessons with a particular student, one individual lesson, or even a specific tune. A new session can be created using the "New" button (Figure 5.3(e)). This opens a dialogue box, allowing the user to save the session with a unique name. Existing sessions can be reopened using the "Open" button (Figure 5.3(e)). Opening an earlier session causes all previous recordings in the session to be loaded into the drop-down selection menu (Figure 5.3(b)) for the corresponding player. Further performances can then be recorded, and are numbered accordingly in the menu. This allows users to revisit

[2] `http://www.juce.com`

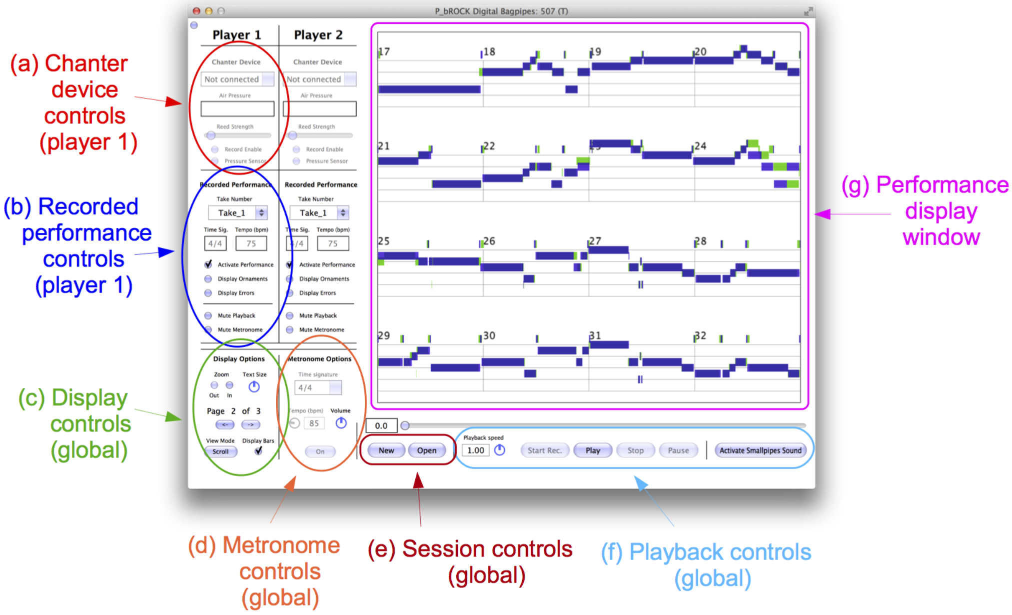


Figure 5.3: Complete GUI window with annotations highlighting different control sections.

and continue previous sessions in order to gauge ongoing progress e.g. with a particular tune.

5.4.1.2 Technical Implementation

Each session corresponds to an individual directory containing all of the performances recorded during that session. Recordings are saved with the file extension ".pbrock"; only files with this extension will be opened by the system. The JUCE `FileChooser` class provides OS-specific dialogue boxes for loading and saving files or directories. When an existing session is opened, all .pbrock recordings in the directory are loaded into vectors corresponding to the player ID (i.e. "Player 1" or "Player 2") by which they were recorded. The contents of each vector are then displayed to the user in a drop-down menu using the `ComboBox` class.

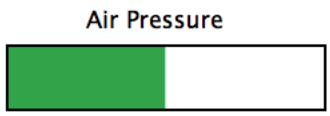


Figure 5.4: GUI air pressure meter showing reading from the digital chanter pressure sensor.

5.4.2 Communication with Digital Chanter Hardware

5.4.2.1 User Controls

The GUI provides individual controls for two separate digital chanter interfaces, allowing two players to use the system simultaneously. The chanter controls for Player 1 are shown in Figure 5.3(a). The "Chanter Device" drop-down menu allows the user to select from a list of all chanters currently connected to the system by USB. If the chanter is being used as part of a full set of bagpipes, the reading from the pressure sensor on the chanter interface is displayed on the GUI by an "Air Pressure" meter, as shown in Figure 5.4. This allows the user to monitor the pressure exerted on the bag in real time. The pressure level at which the drones and chanter sounds are activated can be adjusted using the "Reed Strength" slider.

If the player does not wish to use the pressure sensor function (e.g. in order to use the chanter separately from the rest of the bagpipes), this can be disabled by un-checking the "Pressure Sensor" toggle button (Figure 5.3(a)). In this mode, the chanter will sound whenever any of the holes are covered, and become silent when the player removes all of their fingers from the holes. This allows the sound to be activated and deactivated quickly and easily without unnecessary GUI interaction, and does not cause unintentional silences, since the chanter should never be fully open while playing (as shown by the fingering diagram in Figure 1.2).

5.4.2.2 Technical Implementation

Every digital chanter device connected to the system corresponds to a `Chanter` object in the software. The `Chanter` class is a subclass of JUCE's `Thread` class, meaning that each `Chanter` object runs on a separate thread of execution to the main GUI application. `Chanter` objects are identified using the associated serial port as a unique key. Therefore, while the current GUI only provides controls for two chanter devices, the software framework can theoretically hold any number of `Chanter` objects, and in practice this would be limited only by the number of serial ports available on the host computer.

As described in Section 3.2.3, the digital chanter interface transmits data frames in a packed binary representation at 1ms intervals. Every frame contains a frame number (cyclical from 0 to 16383) and the values from the pressure and tone hole sensors. Each `Chanter` thread monitors the appropriate serial port until a complete frame is received. The frame number is used to ensure that the incoming data has not been corrupted. Should a duplicate frame be detected, it is ignored by the system.

The `Chanter` object contains a unique calibration file which is used to decode the raw sensor data. For each of the tone holes, the `ChanterCalibrator` object returns whether or not the hole is open by comparing the current sensor reading to a predefined threshold value. The `ChanterCalibrator` includes separate thresholds for the pressure sensor readings at which the drones and chanter sounds should be activated; these can be adjusted by the user using the "Reed Strength" slider on the GUI, as described in Section 5.4.2.1.

5.4.3 Recording Performances

5.4.3.1 User Controls

During the pilot study discussed in Section 5.3, the instructor suggested that the ability to record two people playing together would provide a more meaningful comparison of phrasing than could be obtained by recording in turns. The GUI therefore incorporates controls for recording performances from two digital chanters, either simultaneously or individually. To prepare a chanter for recording, the "Record Enable" toggle button for that device should be activated (Figure 5.3(a)). Recording can then be started and stopped using the "Start/Stop Rec." button (Figure 5.3(f)). If the user wishes to record to a metronome, this feature is enabled using the controls shown in Figure 5.3(d). Rotary dials are used to set the metronome volume and tempo (40bpm to 250bpm), and a drop-down menu allows the user to select the time signature ($\frac{2}{4}$, $\frac{3}{4}$, $\frac{4}{4}$, $\frac{6}{8}$ or $\frac{9}{8}$). Furthermore, the system enables the user to record along to previous performances, which are selected using the drop-down menu. This can be disabled by un-checking the "Activate Performance" toggle button (Figure 5.3(b)) prior to recording.

5.4.3.2 Technical Implementation

Section 5.4.2.2 describes how incoming data frames from the digital chanter interface are received and unpacked to retrieve the unique frame number and sensor readings. If the chanter is set to record by the user, then these frames are appended to a vector within a `Performance` object. Each recorded frame is assigned a timestamp, using the frame number to take into account dropped or duplicate frames if any should occur. In addition to the timestamped frames of sensor readings, the `Performance` object stores other relevant information about the recording, such as the metronome settings and `ChanterCalibrator` thresholds used, and whether or not the pressure sensor was employed. The player ID and take number are also saved. Once the recording is complete, the entire `Performance` object is written to an XML file with the extension ".pbrock" in the appropriate directory for the current session, allowing the performance to be reconstructed exactly when the session is reopened.

5.4.4 Playback of Recorded Performances

5.4.4.1 User Controls

Figure 5.3(f) depicts the GUI controls for playback of recorded performances. Playback is started, stopped and paused using the "Play", "Stop" and "Pause" buttons respectively. The starting point for playback can be set to anywhere in the performance by clicking on the staff in the display window (Figure 5.3(g)) or by dragging the time scroller control to the desired position. A rotary dial can be using to adjust the playback speed between $1/4\times$ and $4\times$ the original tempo, and the audio output can be set to either GHB or Scottish Smallpipes sounds (as described in Section 3.3).

Moreover, while not necessarily envisaged as the intended use of the system, it is possible to play two performances with different tempi and time signatures at once. For this reason, each performance has its own metronome. Playback of individual performances and their respective metronome sounds can be enabled and muted using the toggle button controls in Figure 5.3(b).

5.4.4.2 Technical Implementation

Playback of recorded performances is handled by the `Playback` class. Each `Playback` object contains a reference to one `Performance` object at a time, and runs on its own thread of execution. The `Playback` object keeps track of the current timestamp in the performance and determines when to move to the next frame using the system clock provided by the JUCE `Time` class. This allows the playback speed to be adjusted simply by iterating through the millisecond timestamped frames at the appropriate rate. The Open Sound Control (OSC) protocol (Wright & Freed, 1997) is used to communicate playback information to the audio output software, a standalone application written in the SuperCollider language (McCartney, 2002), which is described in Section 3.3.

5.4.5 Visualisation

5.4.5.1 User Controls

Recorded performances are displayed to the user in a dedicated visualisation window (Figure 5.3(g)). Pitch, bar lines and bar numbers are depicted on a traditional staff system, while note duration is represented using a proportional notation, as described in Section 5.1.2. During playback, a playhead scrolls across the staves to illustrate the current playback position. The window can display one performance per player. These are selected using the menu shown in Figure 5.3(b), which shows all performances for that player in the current session. Visualisation of each player's performance is activated/deactivated using the "Activate Performance" toggle buttons.

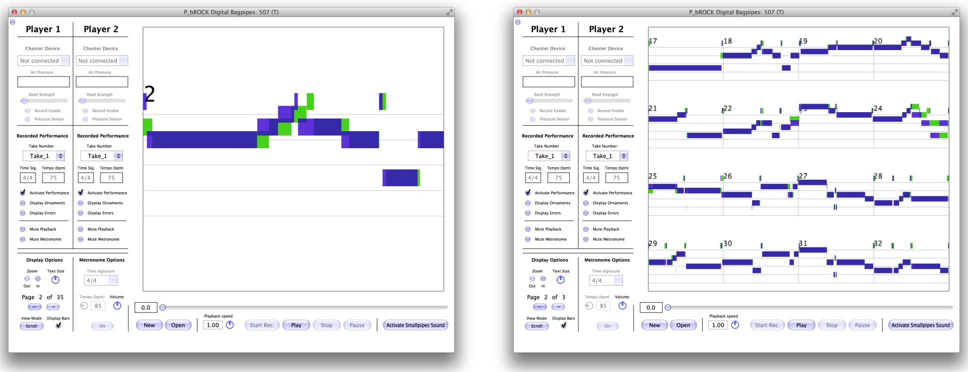


Figure 5.5: Illustration of GUI zoom feature.

The GUI controls for the performance display window are shown in Figure 5.3(c). Longer recordings spanning multiple pages can be navigated using the left and right arrows, and the bar lines and bar numbers can be removed when displaying

Figure 5.6: Scroll view option to display two performances on separate staves.

performances recorded without the metronome. During the pilot study of the prototype system, it was suggested that a zoom feature should be added to allow the user to focus on specific regions of the performance. The “Zoom Out” button automatically increases the number of staves and bars shown, while activating the “Zoom In” toggle button enables the user to zoom into particular sections of the piece by clicking on the display window. This is illustrated in Figure 5.5. The GUI also features a “Scroll View” mode, which allows two performances to be displayed simultaneously on separate staves rather than overlaid, as shown in Figure 5.6.

5.4.5.2 Technical Implementation

The visualisation window is rendered in OpenGL using JUCE’s `OpenGLRenderer` class. To minimise the processor workload involved, the display is not repainted continuously. Instead, the main application monitors any changes (e.g. in the `Playback` or `Performance` objects) which require the display to be updated, then triggers a repaint of the OpenGL window.

5.5 Automatic Ornament and Error Detection Feedback

The prototype system discussed in Section 5.2 was developed solely as a tool to assist an experienced human instructor in describing their own observations to students, and did not include any "intelligent" features for generating automatic feedback. Since the final GUI application is intended for use in both lesson and solo practice situations, it is preferable that the system be able to highlight instances of errors and poor technique to students in the absence of an expert tutor. This section describes the error detection capabilities of the complete GUI program.

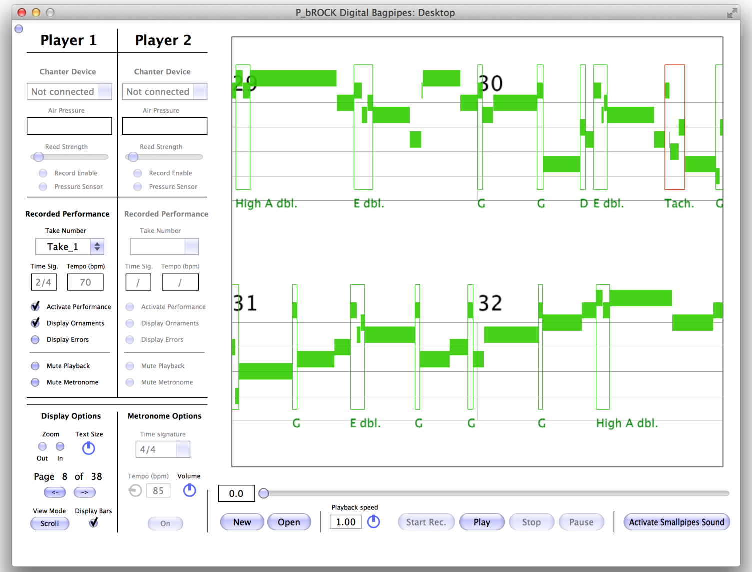
5.5.1 Ornamentation Errors

The GUI system incorporates the OR_{dtw} ornament recognition algorithm described in Chapter 4. This feature is activated using the "Display Ornaments" toggle button (Figure 5.3(c)), which annotates all detected ornaments in the display window, as shown in Figure 5.7. The red rectangle around the *tachum* movement in bar 30 indicates that it contains an error. Clicking on the ornament opens a text window describing the mistake in the embellishment (in this case an additional C gracenote) and highlights the error with a red circle (Figure 5.7(b)).

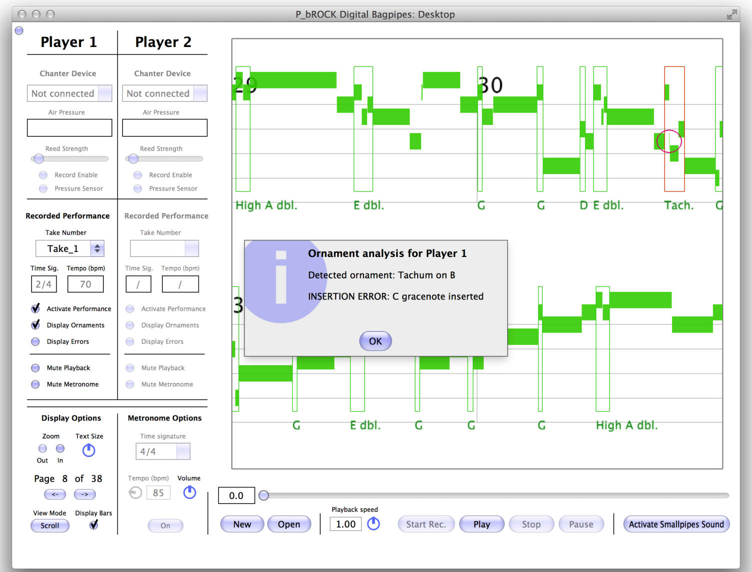
5.5.2 False Fingering Detection

As discussed in Section 1.2.4.1, while the practice of *false fingering* is seen in traditional piping circles as a serious technical flaw, the comparatively subtle differences in pitch and timbre between correct and incorrect fingerings can be difficult to discern. During the pilot study described in Section 5.3, the instructor suggested that the ability to highlight instances of false fingering would be a valuable addition to the system. Since there is only one correct fingering for each of the nine notes in the traditional piping scale, this facility can be implemented conveniently using a simple lookup table approach, in which the correct state of the eight chanter holes is stored for each possible pitch.

Activating the "Display Errors" toggle button (Figure 5.3(c)) causes any note (or section thereof) which is fingered incorrectly to be highlighted in red. Details of the false fingering can be displayed in a text window (Figure 5.8), allowing



(a) Detected ornaments shown in GUI. Red box indicates an ornamentation error.



(b) Feedback window identifying insertion error in ornament (circled in red).

Figure 5.7: GUI showing ornaments detected in performance.

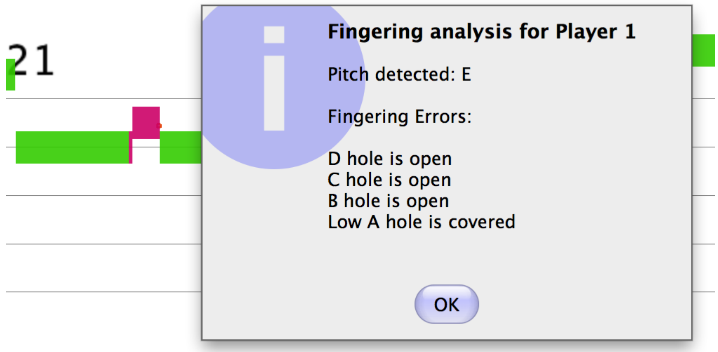


Figure 5.8: False fingering feedback.

the user to identify, recreate and rectify the error. It should be noted that the concept of false fingering applies only to melody notes; gracenotes in an embellishment are usually performed with one finger at a time, and hence often do not correspond to the correct fingering for a given pitch. It is therefore a prerequisite to meaningful false fingering detection that the ornament recognition algorithm performs effectively, to avoid labelling gracenotes as false fingerings.

5.5.3 Crossing Noise Detection

Another common problem among inexperienced pipers is the inclusion of unwanted short notes or *crossing noises* caused by poorly coordinated transitions between fingerings, as described in Section 1.2.4.2. While a crossing noise could theoretically be of any duration, they are generally very short, such that the audible effect is often a “pop” or “blip” rather than a discernible pitch. Automatic detection of crossing noises with arbitrary length would require *a priori* knowledge of the tune being performed. Since the GUI application does not include such knowledge, the error detection approach is based on the premise that incorrect notes of sufficient duration to be manifested as clear pitches would be obvious to the user on playback of the recording, and instead focusses on the detection of short crossing noises which might otherwise be difficult to identify.

The system therefore assumes any note whose duration falls within an empirically determined range $L_{CN1} = 2$ms to $L_{CN2} = 45$ms, and which has not been classed as a gracenote by the ornament recognition algorithm, to be a potential crossing noise. The notes on either side of the possible error are then considered. The

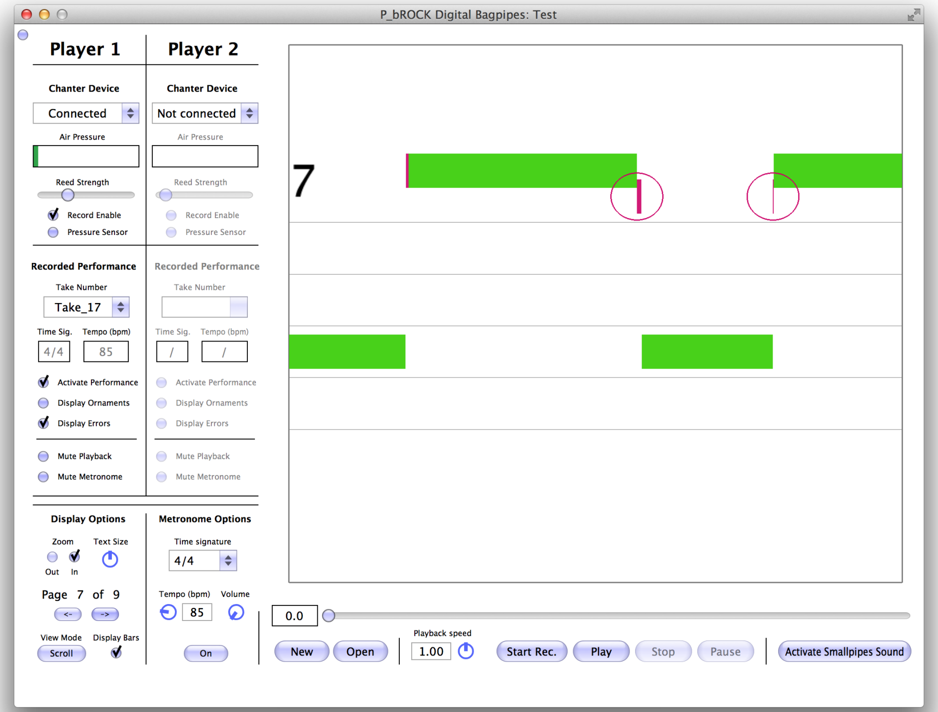


Figure 5.9: "Crossing noise" errors identified by red circles.

nature of GHB fingering (Figure 1.2) implies that transitions from one note to another, however gradual or untidy, should never result in an intermediate state that is higher in pitch than both the previous and subsequent notes. If this should be the case, the note is determined not to be a crossing noise, but rather an attempted *gracenote* which has fallen below the ornament detection threshold L_{min}. Similarly, if the surrounding pitches are identical then the note is classed as a *strike* ornament which has been ignored for the same reason. Otherwise, the crossing noise is identified in the display window by a red circle, as shown in Figure 5.9.

5.6 *Bagpipe Hero*: A Game Interface for Piping Practice

This section describes an alternative GUI system which incorporates the recording and ornament detection facilities into a game format. Loosely inspired by the popular "Guitar Hero" series[3], the *Bagpipe Hero* program allows the user to play along to exemplar recordings of a variety of well known pipe tunes using the digital chanter, and provides a score for accuracy in each case. Section 5.6.1 presents the original motivation for the concept, and some initial observations gathered using an early prototype. The scoring system and user interface for the final *Bagpipe Hero* system are discussed in Sections 5.6.2 and 5.6.3 respectively.

5.6.1 Initial Motivation and Proof of Concept

During the pilot study with the prototype GUI system (Section 5.3), the instructor suggested adding the facility to rate the accuracy of recorded performances numerically. He felt that this would be a useful feature by which students could gauge their progress with a particular tune, and could also introduce a competitive element which might increase motivation to practice amongst the pupils. In response to this suggestion, a quick proof-of-concept prototype was implemented and tested at the end of several sessions during the pilot study.

This prototype of the *Bagpipe Hero* program operates as follows. The GUI features a single staff with a marker displaying the current note being played on the digital chanter. The notes in the template recording (i.e. the tune recorded previously by the instructor) scroll across the screen from right to left, and the player attempts to match them with the marker. At the end of the piece a percentage score is displayed, indicated the number of frames for which the performed pitch matched that of the template.

The reaction from the students was decidedly positive; all stated that they would be more inclined to practice in their own time if the *Bagpipe Hero* system was installed in the school. In particular, when the instructor suggested that if a leader board was set up each time a new tune was introduced to the pipe band, one pupil agreed that the motivation to practice would increase because *"you'd want to beat everyone"*. Other feedback included *"This thing is cool"*, and *"it's a lot of fun; I want one!"*.

An interesting observation made by the instructor regarding the *Bagpipe Hero* system was that several pupils seemed to emulate the template performance significantly more accurately than with the original visualisation (playhead moving through stationary notation). One participant felt that it *"helped quite a lot*

[3] `http://www.guitarhero.com`

because you know how long to hold each note on". Another student, a relative beginner who had been playing for around six months, struggled greatly when recording to the metronome using the standard visualisation scheme, rarely holding the beat for more than a few bars before rushing into the next phrase. Subsequent investigation of the student's first recording of the $\frac{3}{4}$ march "I See Mull" indicated less than 11% accuracy on a frame-by-frame basis. On the next attempt at the same piece using *Bagpipe Hero* mode, the student achieved a score of 65%. The instructor described the second performance as *"an unbelievable difference"*, noting to the pupil *"you started to hold onto the long notes; you were waiting to go"*.

5.6.2 Scoring System

The prototype described in the previous section assigned a percentage score based on a simple frame-by-frame comparison between the recorded performance and the template. While sufficient to gain an initial impression of the students' enthusiasm for the *Bagpipe Hero* concept, this approach does not provide a meaningful assessment of piping technique (e.g. correct execution of embellishments), or indeed of musical performance in general; it is heavily biased towards long held notes, such that a reasonable score could be achieved with little or no attempt at the correct ornamentation or phrasing.

For *Bagpipe Hero* to be of long-term benefit as a practice tool, rather than simply a passing novelty, it is necessary for the scores and feedback generated to show a clear correlation with the accuracy of the player's performance. For this reason, the scoring system used in the final *Bagpipe Hero* program incorporates the ornament and crossing noise detection algorithms in order to reward good piping technique and penalise mistakes. Moreover, the majority of points associated with each note in the template recording are only awarded if the timing of the player's performance falls within a specified margin of error. This section describes the operation of the performance scoring algorithm. The various reward and penalty values given below were determined empirically to provide a moderate level of difficulty; these could of course be adjusted based on the player's experience.

During recording, the percentage score is computed continuously by keeping two running tallies; one detailing the maximum possible result at that moment in the performance, the other enumerating the points accumulated by the player. Since the ornament detection algorithm requires a finished gracenote sequence, the scoring function imposes a deliberate latency behind the most recent frame in the incoming performance. A delay of 1 second was deemed sufficient to distinguish long unbroken sequences of potential gracenotes, while still returning a result in adequate time for the causal effect on the score to be evident to the user.

For each melody note in the template, the player receives a score of $S_n = 1000$ points if the correct pitch is performed within the window $T_n \pm T_d$, where T_n is the onset time of the template note, and the allowed temporal drift $T_d = 80$ms. Correctly matched embellishments performed within $\pm T_d$ milliseconds of the start of the movement receive $S_o = 1000$ points for each note in the template ornament (i.e. *gracenotes* and *strikes* are worth 1000 points, while an accurate *taorluath* earns 4000 points). The score is also incremented by 1 point for each frame in the template for which the pitch is matched. This ensures that the score counter is always increasing while the player is holding a long note, without changing the fact that the correct ornamentation and phrasing is required to achieve an acceptable result.

However, if the player omits an ornament from the template performance, a penalty of $P_{mo} = 1000$ points is incurred. Embellishments which are correctly matched but contain mistakes are penalised by $P_{oe} = 50$ points for each frame of error (i.e. a 10ms insertion error would incur a loss of 500 points). Lastly, a fixed penalty of $P_{cn} = 500$ points is deducted each time a crossing noise is detected in the incoming performance.

5.6.3 User Interface and Gameplay

The aim of the *Bagpipe Hero* program is to generate useful feedback on the player's performance in the context of a fun and engaging game environment, so as to encourage younger learners to practice while rewarding good technique and identifying bad habits. The visual elements of the program were developed using illustrations by writer and cartoonist Cian O'Luanaigh[4]. When the game is launched, a title screen appears as shown in Figure 5.10. Clicking the "Start" button leads to a second page where the player is asked to enter a user name, and to select either the male or female character (Figure 5.11). The following screen, depicted in Figure 5.12, allows the user to choose which tune to play, and whether or not they wish to enable the pressure sensor in order to use the digital chanter with a full GHB set.

[4] `http://www.theguardian.com/profile/cian-o-luanaigh`

Figure 5.10: *Bagpipe Hero* title screen.

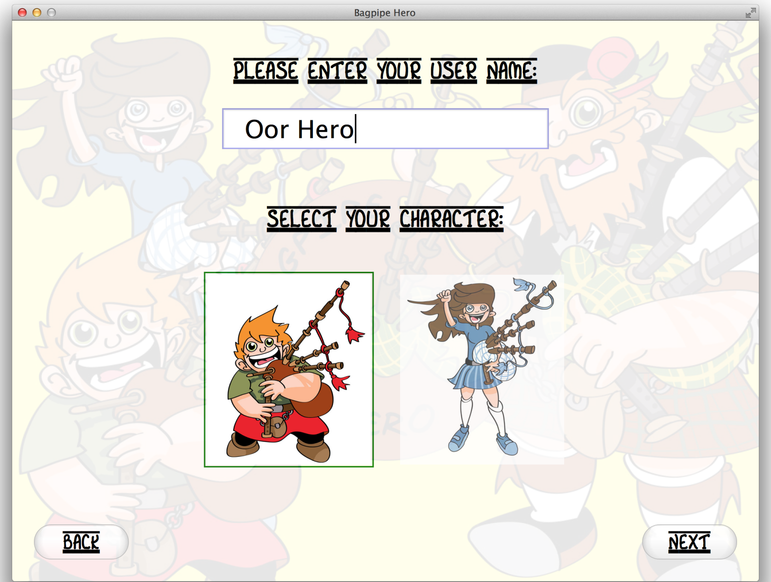


Figure 5.11: User name and character selection screen.

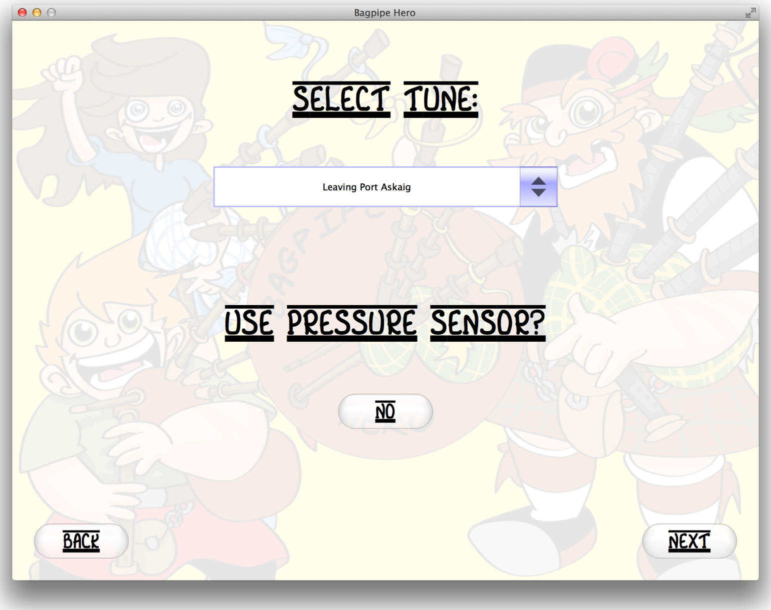


Figure 5.12: *Bagpipe Hero* tune selection screen.

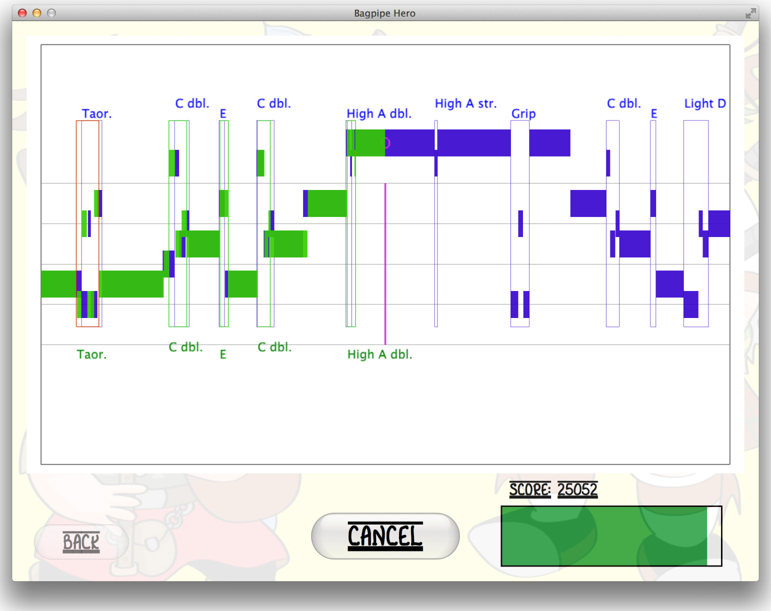


Figure 5.13: *Bagpipe Hero* gameplay screen.

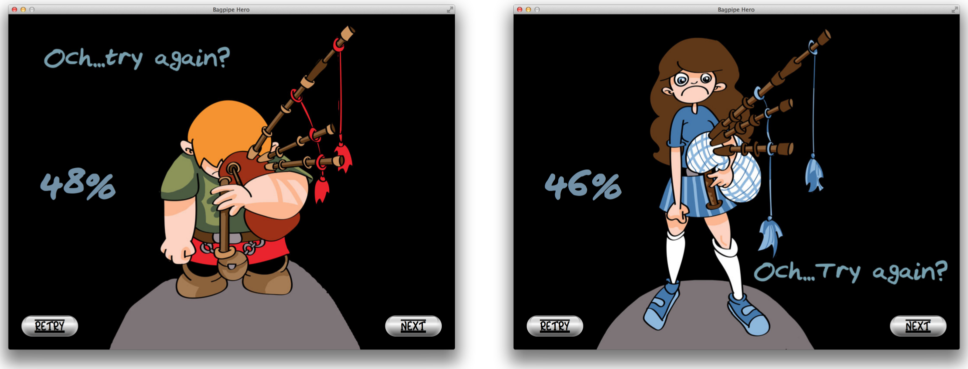


Figure 5.14: *"Och... Try again?"* screens for male and female characters.

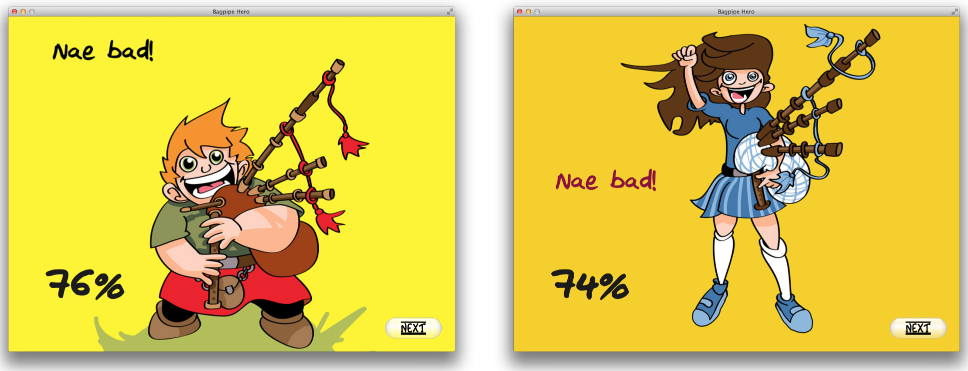


Figure 5.15: *"Nae bad!"* screens for male and female characters.

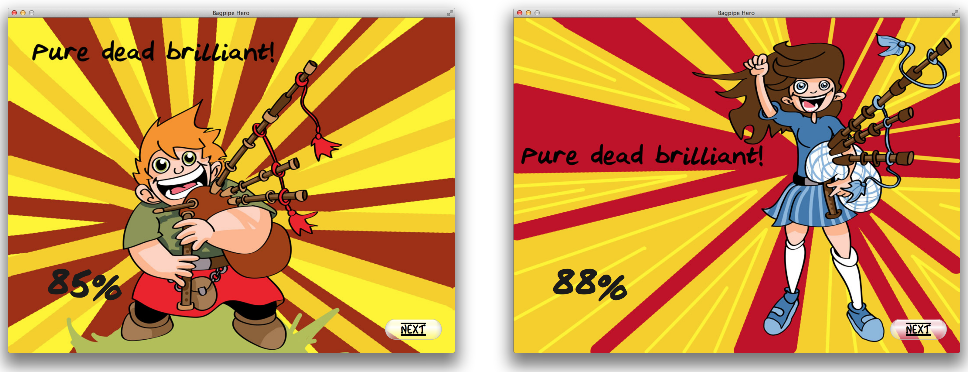


Figure 5.16: *"Pure dead brilliant!"* screens for male and female characters.

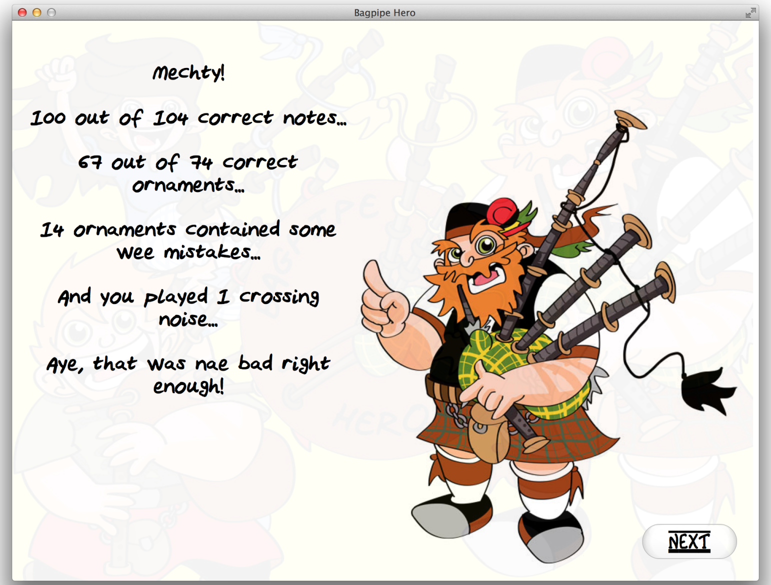


Figure 5.17: *Bagpipe Hero* "instructor" character feedback screen.

Figure 5.18: *Bagpipe Hero* leader board screen.

Having selected a tune, the user is then taken to the main gameplay screen, which is shown in Figure 5.13. When the "Start" button is clicked, the template performance begins to scroll from right to left across the staff, complete with ornament annotations. The purple line in the middle of the stave shows the current point in the piece, and the circular marker indicates the pitch being played on the digital chanter. The score counter is updated continuously as the performance progresses, while the size and colour of the "health bar" (Salen & Zimmerman, 2004) in the bottom right hand corner illustrates the current score as a percentage (green denotes a score $\geq$ 80%, yellow signifies 50%-79%, and red represents a score of less than 50%).

At the end of the piece, the player is presented with one of three screens depending on their final score. For a result less than 50%, the selected character is depicted standing dejectedly against a black background, next to the words *"Och... Try again?"*, as shown in Figure 5.14. If however the player has succeeded in keeping the health bar within the yellow region, the performance is deemed *"Nae bad!"* (Figure 5.15). Scores of 80% or above are given the highest accolade of *"Pure dead brilliant!"*; this is illustrated in Figure 5.16. In the following screen (Figure 5.17), the player is introduced to a third character, the "instructor", who assesses their performance by enumerating the number of correct notes, ornaments and crossing noises. Lastly, a leader board showing the top 5 performances of the chosen piece is displayed, as shown in Figure 5.18.

5.7 Summary

This chapter has provided a detailed description of the GUI application developed during this project. The program uses data from the digital chanter interface (Chapter 3) and incorporates the ornament recognition algorithm presented in Chapter 4, forming a complete hardware and software system to support the GHB learning process. Development of the system was informed by feedback gathered during a pilot study with an early prototype which provided facilities for recording, playback and visualisation of instructor and student performances. The final application features an improved user interface and additional capabilities for automatic error detection. An alternative version of the GUI incorporates these recording and analysis features into a game environment for piping practice, *Bagpipe Hero*. In Chapter 6, the system is evaluated in an series of user studies, in order to examine how such a tool might be used in practice.

Chapter 6

Evaluation

In this chapter, the complete digital chanter hardware and software system presented in the preceding chapters is evaluated in a series of individual studies. Sections 6.2 to 6.5 concern an extended user study which was conducted over a five week period in May-June 2014 to investigate the use of the system in the context of lessons with an experienced instructor. In Section 6.6, the effectiveness of the digital chanter system as a tool for solo practice is considered in a focussed study with four adult pipers. Section 6.7 provides a limited evaluation of the *Bagpipe Hero* program and the perceptual relevance of its performance scoring algorithm.

6.1 Objectives of Evaluation

In broad terms, the purpose of this chapter is to establish the effectiveness of the digital chanter system as a tool to support the GHB learning process. Three separate studies concerning different aspects and use cases of the system are presented. The most extensive of these is the lesson study (Sections 6.2 to 6.5), which will examine how, and to what extent, the instructor chooses to use the various features of the system. By comparing sessions conducted with and without the full GUI system, the effect of the technology on the structure and organisation of the lessons will be investigated.

The smaller-scale evaluation discussed in Section 6.6 aims to determine how the system is incorporated into the practice routines of four adult pipers. Both quantitative (sensor data for recorded performances and logs of GUI program activity) and qualitative (participant responses from surveys and interviews) data will be analysed to assess which features were found to be most/least effective, and how the system usage patterns differ from those observed in the lesson study.

Lastly, the *Bagpipe Hero* application presented in Section 5.6 is considered. The primary aim of *Bagpipe Hero* is to encourage motivation for practice among students. While a detailed investigation of long-term user engagement with the system is beyond the scope of this study, it is likely that players would quickly lose interest if the scores provided by the game did not appear to reward good performances (Richter, Raban, & Rafaeli, 2015); players should be able to see their score increase as their technique improves. For this reason, Section 6.7 describes a listening test which was conducted to inspect the alignment between the *Bagpipe Hero* scoring algorithm and the subjective opinions of human listeners with regard to performance quality.

6.2 Lesson Study: Procedure

6.2.1 Location and Participants

This study was carried out in the same location as the pilot study described in Section 5.3 (a private boarding school in North East Scotland) to assess the value of the system in the context of one-to-one piping lessons. The lessons were conducted by the school's resident piping instructor, an expert piper with approximately 20 years teaching experience.

The instructor initially identified 23 students to take part in the study, which he divided into two broad categories based on their level of piping proficiency; 8 students in the beginner/intermediate range, and 15 more advanced players. Within these two categories, the participants were randomly assigned to one of two groups (hereafter referred to as the *test* and *control* groups), such that each group would contain approximately the same number of students from the two ability classes.

In practice, six students failed to attend any lessons over the course of the study. Of the 17 students who attended at least one lesson, 9 were in the test group and 8 in the control group. The participants were aged between 10 and 17 years old (mean = 13.2 years, σ = 1.9 years) and had been learning the bagpipes for between 4 months and $4\frac{1}{2}$ years (mean = 31.6 months, σ = 15.9 months).

6.2.2 Experimental Setup

The lessons took place as usual in the instructor's office, where the software was installed on a 15" MacBook Pro laptop computer. Within the 30 minute time slots allocated for each session, the average duration of actual lesson content was approximately 20 minutes (mean = 1183 seconds, $\sigma = 289$ seconds). Since not all students attended lessons every week, a total of 36 lessons were conducted as part of the study, of which 17 were in the test group, and 19 in the control group. Most lessons were conducted on a one-to-one basis, though in some instances due to timetabling constraints, two students of a similar level (and from the same experimental group) were taught together. This accounted for six of the 36 lessons.

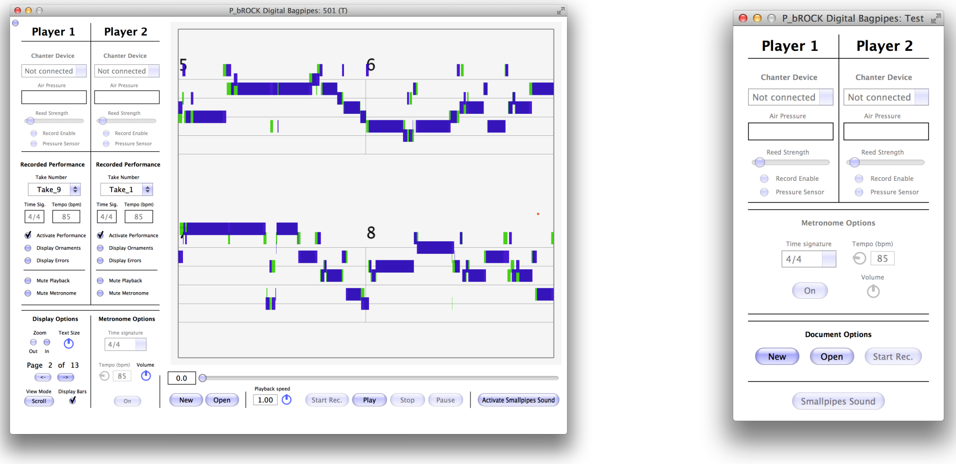
In all of the sessions there were two digital chanters connected to the computer, one each for the instructor and the student. During the lessons where two pupils were present, the instructor would decide how the chanters were shared between the three participants; sometimes the students would take a chanter each, while at other times they shared one and took it in turns to play along with the instructor.

The test group lessons were conducted using the full GUI system, featuring all of the ornament and error detection facilities described in the preceding chapters. To provide a comparative case, the control group used the same digital chanters (so as to remove any potential bias in terms of familiarity with the instrument), but only a very limited GUI without any of the visualisation, analysis or playback capabilities. The two versions of the GUI are shown in Figure 6.1

Prior to the beginning of the study, an introductory session was held with the instructor to allow him to become familiar with the system. In both test and control groups, the instructor was asked to conduct the lessons in whatever manner he chose; in the test group, he was free to refer to the GUI features as much or as little as he wished. The author was present during all sessions to answer questions relating to operation of the system, but otherwise left the organisation of the lessons to the instructor.

6.2.3 Data Collection

In order to allow the interactions between instructor, student(s) and system to be examined in detail, the lessons were video recorded, with an additional audio recorder as a backup. The video camera was positioned behind and to



(a) Full GUI for test group. (b) Control group GUI.

Figure 6.1: Full GUI (test group) and limited GUI (control group).

the side of the laptop, providing a full upper body view of both instructor and student (including faces and hands) when seated in front of the desk. Sensor data from the digital chanters was selectively recorded when enabled by the instructor.

To provide a supplementary means of quantitative analysis, Likert-style surveys were given each student before the first lesson, and after the last lesson. For each question, students were asked to answer 1 ("strongly disagree") to 5 ("strongly agree"). The surveys asked about students' opinions on their own execution of various piping techniques (e.g. ornamentation), general aspects of musical performance (e.g. timing), and the extent to which they believe they are always aware of their own mistakes (e.g. instances of false fingering, crossing noises).

Both introductory and concluding surveys comprised of the same 13 questions for comparison between before and after responses. The concluding survey included a further three questions regarding the experience of using the system, and a free text box for any additional comments. Four students did not attend their last lesson and thus did not complete the final survey; these participants are excluded from the numerical calculations presented in Section 6.3.3. The full introductory and concluding surveys are provided in Appendix C.

Annotation Name	Description
Tutor playing	Tutor is playing digital chanter
Student playing	Student is playing digital chanter
Tutor sings	Tutor sings passage to student
Tutor identifies error	Tutor points out an error without assistance of GUI
System identifies error	Tutor points out an error using the GUI
Tutor correction/action	Description of tutor's actions upon identifying error
Tutor overrides system	Tutor overrules feedback from system
Playback of recording	Playback of recorded performance(s)
Using GUI features	Time spent using the GUI system
Using click/recording	Tutor enables the recording/metronome functions
Comment/discussion about system	Tutor and/or student comment on the system

Table 6.1: Annotation categories used for first pass of video analysis process.

6.2.4 Annotation of Lesson Video Recordings

Any analysis of the video recordings, either quantitative and qualitative, requires an understanding of the various activities carried out in the sessions, and the amount of time spent on each. To obtain this information, the videos were manually annotated using the ELAN[1] Linguistic Annotator program (v. 4.7.2). Due to the inherent difficulty of predicting how best to classify a complex series of human (and computer) interactions, the lessons were annotated using an iterative approach, starting with a broad overview of the observed activities before looking in greater detail at specific areas of interest. This first round of annotations, which took approximately five weeks, identified and classified lesson activities using the categories shown in Table 6.1.

One of the primary objectives of the video analysis was to document every instance in which the tutor points out an error in the student's playing, either with or without the assistance of the GUI system. During the first pass of the annotation process, the type of error in each case was classified according to the seven categories shown in Table 6.2.

Following the first pass of video analysis, preliminary investigation of the resulting annotations indicated that the "Ornament error" category accounted for a significant majority of the total number of errors identified during the lessons. This category was therefore divided into a number of subcategories to clarify the precise nature of the ornament error (such as wrong/missing/extra notes in

[1] `http://tla.mpi.nl/tools/tla-tools/elan/`

Error Category	Description
False fingering	False fingering error identified
Crossing noise	Crossing noise identified
Wrong ornament	Different ornament to that shown in music
Ornament error	Error(s) identified in execution of ornament
Note/tune error	Wrong melody note(s) identified
Timing error	Error relating to timing/phrasing identified
General scrappiness	Insufficient feedback provided for further classification

Table 6.2: Error categories used for first pass of video analysis process.

the ornament, problems with timing/phrasing etc.) The full list of refined error categories is shown in Table 6.3.

Furthermore, it was observed that the annotation categories "Tutor identifies error" and "System identifies error" were not sufficiently clear in certain situations (such as those in which the instructor would report having noticed an error, then refer to the GUI to identify it). These categories were therefore subdivided to address this issue, giving the final list of annotation categories detailed in Table 6.4.

6.2.5 Analysis of Survey Responses

The purpose of the Likert-style questionnaires given to participants before and after the study was to try to identify any patterns in how the students' perception of their own playing changed over the course of the sessions. Of particular interest are the first eight questions in the survey, which consider the extent to which students feel able to execute various techniques easily, and their awareness of any errors in their performance should they occur.

While it is unlikely that the results of this survey should demonstrate meaningful statistical significance with such a small sample size, it is nonetheless useful to have some numerical measure of the likelihood that any given outcome derives from more than simply random chance. For this reason, a number of statistical tests were carried out using the responses from the thirteen students who completed both the introductory and concluding surveys. For each question, the following tests were computed (the results of which are presented in Section 6.3.3):

1. Paired-sample t-test between the before and after responses for all students in each experimental group.

Error Category
Ornament Errors:
[OE - Crossing noise in ornament]
[OE - Missing note in ornament]
[OE - Extra note in ornament]
[OE - Wrong note in ornament]
[OE - Generally poor execution]
[OE - Ornament becoming confused with melody notes]
[OE - Timing/phrasing of ornament incorrect]
[WO - Wrong ornament played]
[MO - Missing ornament]
[EO - Extra ornament]
Fingering Errors:
[FF - False fingering]
[CN - Crossing noise]
Other Errors:
[TE - Timing error]
[ME - Melody error]
[GS - General scrappiness]
[SS - Student gets stuck]
[SI - Strike in]

Table 6.3: Refined error annotation categories.

Annotation Name
Tutor playing
Student playing
Tutor sings
Tutor identifies error without GUI
Tutor identifies error and refers to GUI
Tutor identifies error and refers to playback
GUI reveals error
Playback reveals error
Tutor correction/action
Tutor overrides system
Playback of recording
Using GUI features
Using click/recording
Comment/discussion about system

Table 6.4: Refined annotation categories used in second pass of video analysis process.

2. Unpaired t-test of all before/after differences between the two experimental groups.

6.3 Lesson Study: Numerical Results

The following sections present the quantitative results obtained from the lessons. Section 6.3.1 concerns the errors identified in the students' performances as observed during the video analysis, detailing the total number of errors found in the various categories, and the average duration of the subsequent discussion for the different experimental conditions. Section 6.3.2 describes the amount of time the participants spent playing the digital chanters, both individually and together. The numerical responses to the Likert-style questionnaires completed by the students are presented in Section 6.3.3. The implications of these results are discussed later in 6.5.

6.3.1 Student Errors Identified in Lesson Video Annotations

Table 6.5 shows the total number of instances in which each type of error was identified by the instructor over the course of the sessions. In the test group, these are divided into 5 categories:

1. **Tutor**: errors identified by the instructor without any reference to the GUI system.
2. **GUI**: errors pointed out by the instructor after consulting the GUI.
3. **Pb**: errors pointed out by the instructor which were revealed during playback of the recorded performance.
4. **T→GUI**: instances in which the instructor reported being aware of a particular error, then consulted the GUI to locate/examine it.
5. **T→Pb**: instances in which the instructor reported being aware of a particular error, then employed the playback function to locate/examine it.

It should be noted that the GUI category does not report all instances in which an error was detected by the system or displayed on the screen, but only those in which the instructor chose to act upon the feedback provided by the system and communicate this to the student.

Error type	Control	Test Group					
	Tutor	**All**	**Tutor**	**T→GUI**	**T→Pb**	**GUI**	**Pb**
Crossing noise in ornament	21	12	6	1	0	3	2
Missing note in ornament	34	19	13	2	0	0	4
Extra note in ornament	20	8	8	0	0	0	0
Wrong note in ornament	9	0	0	0	0	0	0
Generally poor ornament	110	53	20	0	2	2	29
Ornament/tune confusion	2	0	0	0	0	0	0
Ornament timing/phrasing	9	6	5	0	0	0	1
Wrong ornament	28	17	13	1	0	1	2
Missing ornament	12	4	4	0	0	0	0
Extra ornament	18	3	3	0	0	0	0
All ornament errors	**263**	**122**	**72**	**4**	**2**	**6**	**38**
False fingering	26	46*	0	1	0	45*	0
Crossing noise	20	24	3	0	0	19	2
All fingering errors	**46**	**70***	**3**	**1**	**0**	**64***	**2**
Timing error	34	43	30	2	0	6	5
Melody error	74	33	28	0	0	1	4
General scrappiness	10	6	3	0	0	0	3
Student gets stuck	6	3	3	0	0	0	0
Strike in	1	0	0	0	0	0	0
All other errors	**125**	**85**	**64**	**2**	**0**	**7**	**12**
ALL ERRORS	**434**	**277***	**139**	**7**	**2**	**77***	**52**
Total minutes of lesson	374	336					
Mean no. errors/minute	**1.16**	**0.82**	**0.41**	**0.02**	**0.01**	**0.23**	**0.15**

Of which 13 determined to be over-sized gracenotes.

Table 6.5: Errors identified across all lessons in control and test groups. T→GUI refers situations to where the instructor reported having noticed an error, then used the GUI performance display to identify it; T→Pb refers to situations where the instructor used the playback function to find a particular error.

From the results shown in Table 6.5, some initial observations can be made. Firstly, it can be seen that significantly more instances of error were pointed out in the control group lessons (434) than in the test group (277). Normalised to the total number of lesson minutes in each group, this equates to 1.16 errors per minute in the control group, and 0.82 in the test group.

In both control and test groups, ornament-related errors are the most common type of mistake identified, accounting for 61% of errors in the control group, and 44% in the test group. Of the 122 ornament errors identified in the test

Week	False Fingerings		Crossing Noises	
	Control	Test	Control	Test
1	4/4	16/6	4/4	14/6
2	0/4	0/0	4/4	0/0
3	12/4	15/6	6/4	6/6
4	10/6	11/3	5/6	3/3
5	0/1	4/2	1/1	1/2

Table 6.6: Number of fingering errors identified each week against the number of lessons in each week.

group, only 6 were initially found using the GUI, while 38 were identified during playback of a recorded performance. The majority of ornament errors, even in the test group, were identified by the instructor with no reference to the GUI.

Conversely however, in the "fingering errors" category (i.e. false fingerings and crossing noises), significantly more errors were identified in the test group (70 instances) than the control group (46 instances). For both false fingerings and crossing noises, the majority of instances were found using the error detection facility on the GUI. Upon closer inspection by the instructor, 13 of the 45 instances of false fingering identified by the GUI were determined to be attempted gracenotes, which were too long to be detected by the ornament recognition algorithm. In such cases, the instructor was able to provide feedback tailored to the student's level of experience. Beginning players were advised that it is better to exaggerate than to rush embellishments, and hence they should not consider this as a serious mistake in their playing at this stage, while more advanced students were simply instructed that the gracenote was "too long". Errors related to timing were also more common in the test group (43 instances) than the control group (34 instances).

Table 6.6 shows the number of fingering errors identified in each experimental group against the number of lessons for each week. In the case of false fingerings, it can be seen that significantly more instances are identified in the control group in later weeks, while the test group is more consistent across the duration. Meanwhile, for crossing noise errors the number of instances identified per week in the control group does not exhibit significant variation, while in the test group the number of instances decreased over the course of the study.

Table 6.7 shows the average length of time spent discussing individual errors identified with and without the assistance of the GUI system. The mean duration

Group	Error	Mean Duration
Control	Tutor	13s
Test	Tutor	12s
	GUI	23s

Table 6.7: Mean length of time spent discussing errors identified with and without the GUI system.

Group	Playing	Percentage of Total Lesson Time
Control	Individual	44.6%
	Together	12.9%
	Total	**58%**
Test	Individual	18.8%
	Together	21.5%
	Total	**40%**

Table 6.8: Percentage of total lesson time spent playing digital chanters individually and together in control and test groups.

of such discussions for errors found by the instructor without the GUI was similar for test and control groups (12 and 13 seconds respectively), while errors detected using the system took more time on average (23 seconds). The implications of these results are considered in Section 6.5.

6.3.2 Time Spent Playing Digital Chanters

Tables 6.8 and 6.9 show the amount of time spent playing the digital chanters individually and synchronously (i.e. instructor and student together), as percentages of the total lesson time and total playing time respectively. From both tables it is clear that solo playing is more common in the control group, while the majority of playing instances in the test group are simultaneous. It can also be observed that the overall percentage of time spent playing in the control group is higher than the test group, and that the percentage of synchronous playing in test group lessons increases steadily over the duration of the study. These observations are discussed further in Section 6.5.

Group	Playing	Week					
		1	2	3	4	5	All
Control	**Individual**	49.2%	89.6%	98.2%	70.8%	91.5%	**77.5%**
	Together	50.8%	10.4%	1.8%	29.2%	8.5%	**22.5%**
Test	**Individual**	55.1%	/	47.8%	36.6%	35.0%	**46.7%**
	Together	44.9%	/	52.2%	63.4%	65.0%	**53.3%**
Both	**Individual**	52.3%	89.6%	73.9%	62.2%	58.6%	**65.6%**
	Together	47.7%	10.4%	26.1%	37.8%	41.4%	**34.4%**

Table 6.9: Percentage of total playing time for individual and synchronous playing of digital chanters in lessons.

Question	Test Group			Control Group		
	Before	After	Diff.	Before	After	Diff.
1. Easy to play in time	4.0	4.0	0.0	4.1	4.0	-0.1
2. Aware of timing errors	3.4	3.4	0.0	3.8	4.0	0.2
3. Easy to play ornaments	3.2	3.4	0.2	3.1	3.6	0.5
4. Aware of ornament errors	3.4	3.4	0.0	3.4	4.0	0.6
5. Easy to avoid CNs*	4.0	3.6	-0.4	4.4	4.1	-0.3
6. Aware of CNs	4.4	3.6	-0.8	4.1	4.6	0.5
7. Easy to avoid FFs**	3.4	3.0	-0.4	3.5	3.9	0.4
8. Aware of FFs	3.4	3.6	0.2	3.9	4.1	0.2
9. Enjoy practicing	4.0	4.4	0.4	4.8	4.6	-0.2
10. Enjoy weekly lessons	4.6	4.4	-0.2	4.6	4.6	0.0
11. Enjoy pipe band	4.0	4.0	0.0	4.4	4.4	0.0
12. Enjoy playing solo	3.8	3.4	-0.4	3.6	4.1	0.5
13. Motivated to improve	4.0	4.2	0.2	4.5	4.6	0.1
14. Chanter felt realistic	/	4.0	/	/	4.5	/
15. Chanter was fun to use	/	4.6	/	/	4.6	/
16. Useful as practice tool	/	4.8	/	/	4.8	/

Table 6.10: Mean survey responses from participants before and after lesson study (*CN = crossing noise, **FF = false fingering).

Q	Test Group			Control Group			Both Groups		
	t	σ	p	t	σ	p	t	σ	p
1	0.000	0.707	1.000	0.552	0.641	0.598	0.433	0.641	0.673
2	/	0.000	/	-0.798	0.886	0.451	-0.805	0.689	0.436
3	-0.343	1.304	0.749	-2.646*	0.535	0.033	-1.595	0.870	0.137
4	0.000	1.225	1.000	-1.488	1.188	0.180	-1.163	1.193	0.268
5	1.633	0.548	0.178	1.000	0.707	0.351	1.760	0.630	0.104
6	1.633	1.095	0.178	-1.871	0.756	0.104	0.000	1.080	1.000
7	0.785	1.140	0.477	-2.049	0.518	0.080	-0.322	0.862	0.753
8	-0.408	1.095	0.704	-0.552	1.282	0.598	-0.714	1.166	0.489
9	-1.633	0.548	0.178	0.424	0.835	0.685	-0.365	0.760	0.721
10	0.408	1.095	0.704	/	0.000	/	0.433	0.641	0.673
11	0.000	0.707	1.000	/	0.000	/	0.000	0.408	1.000
12	1.633	0.548	0.178	-1.528	0.926	0.171	-0.617	0.899	0.549
13	-1.000	0.447	0.374	-1.000	0.354	0.351	-1.477	0.376	0.165

Table 6.11: Paired-sample t-tests on introductory and concluding survey responses ($*p < 0.05$).

6.3.3 Student Survey Responses

Table 6.10 shows the mean responses to the Likert-style surveys from all students who completed both the introductory and concluding questionnaires. The first column provides an abridged rendering of each question; the full surveys can be found in Appendix C. Table 6.11 presents the results of the paired-sample t-tests between the before and after responses for participants in each experimental group. The p-values for the unpaired t-tests between the before/after differences in the test and control groups are shown in Table 6.12.

Of the total 52 t-tests performed, only 2 results reject the null hypothesis at the default significance level ($p < 0.05$), which implies that none of the results demonstrate true statistical significance. This is perhaps unsurprising given the small sample size (only 13 students completed both introductory and concluding surveys) and the level of uncertainty associated with human responses of this kind. For this reason, the effect of the system on the lesson environment will be discussed primarily in terms of the observations made by the instructor during the sessions, and measurable differences in playing behaviour. Some limited reflections on these survey results are given in Section 6.5.3.

Question	**p value**
1	0.7481
2	0.5478
3	0.5682
4	0.3810
5	0.6950
6	0.0270*
7	0.1181

Question	**p value**
8	0.9439
9	0.2411
10	0.6059
11	1
12	0.0769
13	0.7424

Table 6.12: Results of independent unpaired samples t-test for all before/after differences between control and test groups ($*p < 0.05$).

6.4 Lesson Study: Case Studies of System Use

This section provides a detailed analysis of four individual excerpts from the video recorded lessons, each illustrating a different pattern of interaction between the teacher, the pupil and the GUI system. In each case, an error is identified in the student's playing and is then addressed by the instructor. The purpose of this section is to highlight the various ways in which the system was observed to contribute to this process during the study.

The dialogue from each excerpt was transcribed according to the conventions described in (Sacks et al., 1974); the symbols and notations used in this work are explained in Figure 6.2. Instances of participants playing on the digital chanters are transcribed using a subset of the notation developed by Duffy and Healey (2013) to represent musical sounds, adapted to suit GHB music; these are shown in Figure 6.3.

Additionally, quotation marks are used here to distinguish vocal sounds which are sung rather than spoken. In these instances, lower case text gives an impression of the sounds made by the singer, while upper case letters indicate that the singer actually sang the name of the note.

The excerpts are transcribed in this way so as to provide the reader with a description of the scene that is as complete and unadulterated as possible while still maintaining a reasonable level of legibility. It should be noted that these case studies are not a rigorous implementation of formal conversation analysis practice, nor will the significance of subtle physical actions such as gaze or facial expressions be explored in any depth. While a thorough examination of these low-level interactions would undoubtedly yield a more nuanced comprehension of the communicative activity in these specific instances, this study instead focuses

[	Beginning of overlap
]	End of overlap
(0.8)	Elapsed time in seconds, to the nearest tenth of a second (used to denote pauses and silences)
(.)	Brief interval (± a tenth of a second) between utterances
-	Indicates a cut-off
=	Latching (no break or gap between two utterances by different speakers)
( )	Empty parenthesis indicate an utterance which could not be clearly heard
(word)	Words in parenthesis indicate the transcriber is unsure of what was said
((laughs))	Double parenthesis indicate features other than verbalisation

Figure 6.2: Dialogue transcription conventions from (Sacks et al., 1974).

E_________(1.8)	Long single note and duration
D_E_lG_hA_(2.3)	Short notes in a musical phrase (lG refers to Low G, hA to High A etc.)
*E________(1.6)	* on a note indicates false fingering
<G>	Gracenote of the given pitch
<s>E_	Strike on following note (E)
<dbl>B_	Doubling ornament on following note (B)
<grip>	Correctly executed grip ornament
<*grip>	* in an ornament indicates incorrect execution

Figure 6.3: Musical transcription conventions adapted from (Duffy & Healey, 2013) for GHB music. These are used to transcribe instances of participants playing the digital chanters.

on the observable behaviours exhibited by the participants in order to obtain a relatively high-level understanding of the different ways in which the GUI system can contribute to the lesson environment.

6.4.1 Case Study 1: Error Identified by Tutor

In this example, the tutor (T) is already aware of the exact nature of a false fingering error in the previous performance by the student (S). This performance was recorded by the system with T and S playing simultaneously. While S was playing, T became aware that S was repeatedly false fingering the note E in a particular phrase. Examination of the video showed the error to be clearly

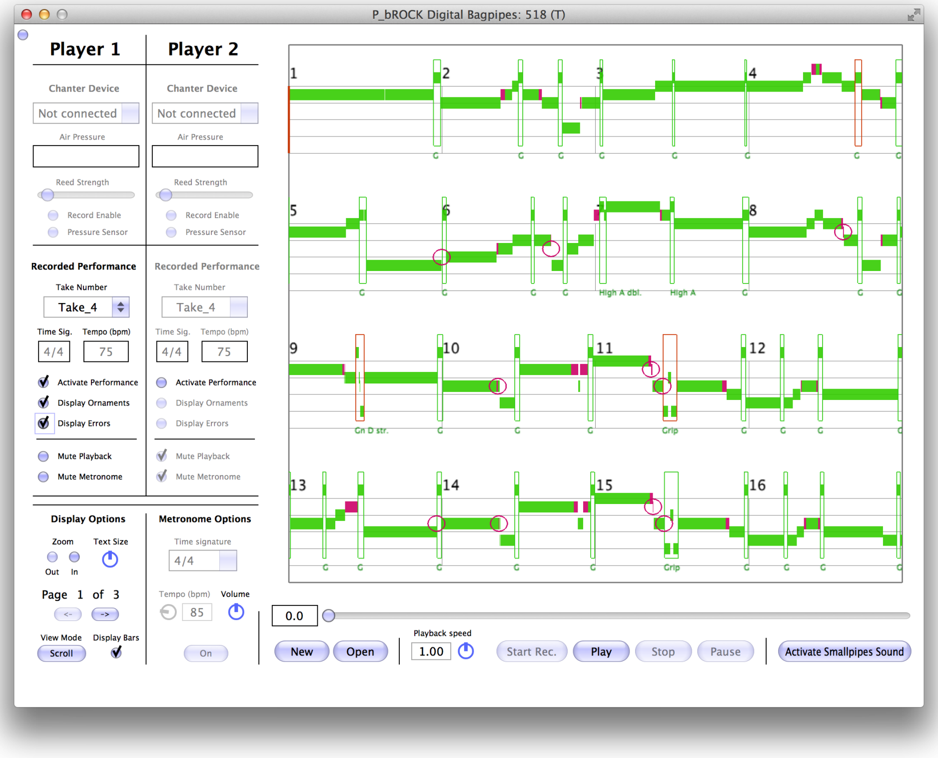


Figure 6.4: GUI showing false fingering error detected in Case Study 1 (bar 13).

visible; S did not move any of the bottom hand fingers when changing between the notes D and E. However, T does not mention the mistake immediately, and S continues to play to the end of the piece. T then clicks on the error on the performance display (bar 13 in Figure 6.4) to bring up the text window before beginning to discuss the error. Transcript 6.1 shows the moment when T first points out the location and nature of the mistake to S.

1. T: okay? right (1.0) [see this one- see this note here? (0.8)
[((T indicates red highlighted note on GUI
with cursor))
2. T: I know exactly what it's gonna say (2.4)

T clicks on note with mouse to bring up text window, and sits back.
T and S both look at text window.

3. T: [okay? [(1.3) so it's- it's detected the note "E" (0.4)
[((T sits forward and looks at S))

```
             [((S nods))
4. T: which is the n- right note that you’re supposed to be
      playing (0.7)

T looks at text window showing precise details of fingering error.

5. T: but it’s fingering errors (0.6) okay? (1.8)
```

Transcript 6.1: T points out false fingering to S using the performance display.

After illustrating the location of the error using the performance display (Transcript 6.1), T then picks up the digital chanter and holds it up towards S. T plays the phrase three times while singing along, twice with the fingering error, then with the correct fingering. This is shown in Transcript 6.2.

```
6. T: and it’s because you’ve played you’ve- you’ve gone ((sings))
      ["C C D (0.7)"
   T: [<G>C_<G>C_D_ (0.7)

T looks up at S.

7. T: ["E" [(1.3)
   T: [*E___((note held))
           [((T waves three fingers of right hand which are
             wrongly positioned))
8. T: you’ve kept it there [(.)
                           [((S looks up at T and nods))
9. T: and then done a gracenote to ((sings)) ["B" (0.9)
   T: ______________________________________ [<G>B___((note held))

T plays and sings false fingered passage again while looking at S.
S watches T’s hands.

10. T: right ((sings)) ["ta ta ah E (0.3) toh"
    T: _______________ [<G>C_<G>C_D_*E_<G>B_

T quickly repeats phrase with correct fingering.

11. T: instead of going ((sings)) ["ta ta ah E"  [(0.6)
    T: __________________________ [<G>C_<G>C_D_E_[((T pauses on
                                                   true fingering))
12. T: ["toh" (0.8) see the difference there?
       [<G>B_____((note held))
       [((T nods on transition to last note))
```

```
13. S: yeah
```

Transcript 6.2: T describes and demonstrates fingering error on chanter.

Having demonstrated both the fingering error and the correct fingering for the phrase in question, T puts down the digital chanter. He then uses the mouse cursor to point out the mistake on the performance display again, as illustrated in Transcript 6.3.

```
14. T: so [(.) that's what it's de- it's- that's what it's
               detected there in your (0.5)
          [((T puts down chanter and looks at GUI))
15. T: on your playing (0.4)
16. T: so [that- that bit there (0.3)
          [((T uses mouse cursor to point to error on display))
17. T: that red bit there ((sings)) "ta ta ah" (0.3)
18. T: "E (0.3) toh" [right? [(1.5)
                     [((T looks at S))
                             [((S nods))
19. T: it's a false fingering
```

Transcript 6.3: T reasserts that the system has detected the error.

The tutor's decision to use the GUI feedback in describing the mistake, despite already being aware of exactly what S had played, suggests that T sees some value in corroborating his observations with evidence from the system. It may be that this provides an additional layer of reliability for S; both the instructor and the computer have detected the error independently. This interpretation is supported by the dialogue in lines 14-19 (Transcript 6.3), in which T reasserts that the system has identified the mistake (*"that's what it's detected there in your playing [...] it's a false fingering"*).

6.4.2 Case Study 2: Error Identified by System

In this example, T and S have recorded a performance simultaneously and are examining it using the performance display. T did not give any indication that he was aware of a fingering mistake during or after the recording. Upon activating the error detection facility, a false fingering error becomes apparent; this error is shown in Figure 6.5 (bar 26). As in the previous example, T opens the text window then waits for S to read the textual feedback before demonstrating the error. Based on the system's fingering analysis, T is immediately able to

Figure 6.5: GUI showing false fingering error detected in Case Study 2 (bar 26).

demonstrate the error in isolation. T then uses the playback facility in order to situate the false fingering in the context of the tune. Transcript 6.4 shows the point where T finds the error on the GUI, and demonstrates it to S.

```
1. T: right (1.5) [so likes a that (5.6)
                  [((T indicates red highlighted note with cursor
                   and clicks it to bring up text window))

T and S both look at text window feedback for several seconds.

2. T: so [you've got- you're playing High A (0.5)
   T:    [hA_____((note held))
         [((T picks up chanter and plays High A))

3. T: but your- your [to- your E finger's off the hole (5.2)
   T: _______________[*hA_____((note held))
                     [((T looks at S and lifts E finger))

S plays High A, High G and F repeatedly; T watches S' hands.
```

```
4. S: hA_hG_F_hA_hG_F_hA_hG_F_[hA_hG_F_ (5.8)
                              [((T puts down chanter and looks
                               at GUI))
5. T: okay? (6.4)
```

Transcript 6.4: T identifies an error using the performance display.

S then attempts to change the subject to a different technique, the *throw on D*. However, T activates the performance playback facility, interrupting S and returning the discussion to the false fingering error. This is shown in Transcript 6.5.

```
6. T: [right (look) right]
7. S: [I swear I've got a] f- I can't play (0.7) a D throw (0.5)
8. S: I've got some- [my fingers, when I do it- (3.6)
                     [((T starts playback))

T and S listen to playback of false fingered passage.

9. T: okay? (2.1)

T stops playback after the error has passed.

10. T: okay [so] that- that bit there (you do)
11. S:      [(what)]
12. S: mm-hmm

T looks at S and plays phrase twice on chanter.
S watches T's hands.

13: T: E_<s>E_hA_<s>A_E_<s>E_[*hA_____ ((note held))
    T:                       [you were like that (0.3)
                             [((T pauses on false-fingered
                              High A))
14. T: you're in mid air
```

Transcript 6.5: T interrupts S by using playback facility to situate error in context of the tune.

After situating the error in the context of the tune using the playback function, T demonstrates the complete phrase on the digital chanter, pausing on the false-fingered High A (Transcript 6.5, line 13). This moment is shown in Figure 6.6.

Figure 6.6: “You were like that: you’re in mid air”.

This case study illustrates several interesting points regarding the usage of the system in the lesson environment. Firstly, in the preceding video footage T made no indication, either verbal or physical (e.g. change of facial expression) that he had noticed the false fingering in S’ playing. This implies that the system can identify certain genuine technical errors that even an experienced instructor might miss if he/she is not watching the student’s hands (as discussed in Section 1.2.4.1, false fingerings are difficult or impossible to identify aurally on an acoustic chanter).

Moreover, this excerpt illustrates the use of multiple system features (the recording function to capture the performance; the error detection and feedback tools to identify the error; and the performance display navigation and playback facilities to listen to the passage in question). This suggests that T had developed a thorough understanding of the affordances and operation of the system by this point in the study (week 5). Lastly, when S attempted to talk over T and change the subject of the discussion, the computer was used by T as a tool to control the flow of the conversation.

6.4.3 Case Study 3: Error Identified During Playback

In this example, T and S are listening to the performance recorded by S, while watching the playhead scroll through the display. In line 1, T identifies an issue with S’ execution of the *grip* ornament, then allows the playback to continue to the end of the recording. After demonstrating the correct technique for the *grip* movement and asking S to repeat it, T returns to the GUI and uses the display to compare the poorly executed ornament with a better example, based on their appearance on the screen. Transcript 6.6 shows the point where T identifies the error while listening to the recorded performance.

```
1. T: right [you're playing your grips funny (.)
            [((T leans forward, raises right arm towards screen))
2. T: [see how- if you look at the g- shape] of your grips (24.7)
      [((T points at screen with right hand))]
```

Transcript 6.6: T identifies poorly executed *grip* during playback.

T then sits back in his chair, and both he and S continue to listen to the remainder of the recording. Once the playback has finished, T picks up the digital chanter and demonstrates the correct execution of the *grip* ornament between the notes B and C (notation shown in Figure 6.7). T then asks S to play the phrase. Transcript 6.7 continues from the end of the playback.

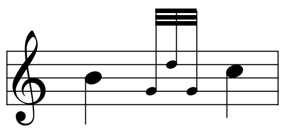


Figure 6.7: Notation for *grip* ornament between B and C.

```
3. T: right there was a wee bit-
      a wee bit of [stuff we can work on there (0.3)
                   [((T sits forward, picks up chanter))
4. T: watch- now [watch your grips
                 [((T turns towards S))
5. T: <G>lA_B_<grip>C___(0.6)
6. T: <G>lA_B_<grip>C_[B_lG_B_lG_]<grip>C___((note held))
   T:                 [you must hit that low G first] (1.1)
7. T: before you [do the D- do the gracenote and come up=
                 [lG_<grip>C___((note held))
8. S: =('kay / yeah) (1.8)
9. T: <G>lA_B_<grip>[C_____(0.9)
                    [((T stamps foot on note C))
10. T: okay? [try that (0.4) ((sings)) "tum ba badahum" (3.1)
```

Figure 6.8: The good and bad *grip* ornaments identified by the instructor in Case Study 3 are shown in blue and red boxes respectively (the boxes were added manually by the author for illustrative purposes).

[((T removes hands from chanter to mute sound))

Transcript 6.7: T demonstrates *grip* then asks S to play the same phrase.

T watches S' hands as she practices the phrase with the *grip* ornaments. T then turns towards to the screen and points to the poorly executed grip on the performance display (bar 42 in Figure 6.8). This interaction is shown in Transcript 6.8.

11. S: <G>lA_B_<grip>C___[___(1.1)
12. T: [right and again
13. S: [<G>lA]_B_<grip>C________(1.7)
14. T: ["tum" ((singing))] (1.3)
15. T: so you've gottae get that- that movement coming through (.)
16. T: okay? you can see, (3.2)

```
T looks towards screen and leans forward.

17. T: [it was frae (8.2)
       [((T moves hand up to control mouse cursor))

T clicks mouse button twice to navigate performance display.

18. T: yeah [likes a here (0.6)
            [((T raises right hand to point at screen))
19. T: see that- see you're coming up to the B? (0.5) but then (.)
20. T: eh you're hitting the D gracenote- you're not- before
       you're in on the low G (0.6)
```

Transcript 6.8: S practices phrase and T finds example of poorly executed *grip* on performance display.

Having illustrated the problem with S' *grip* ornament using the performance display, T demonstrates the error twice using the digital chanter, before demonstrating the correct execution a further two times. T then points to the performance display to compare the visual appearance of the good and bad *grips*, as shown in Transcript 6.9.

```
21. S: [mm-hmm]
22. T: [so you're doing a] (.)
23. T: so you're- [you're going from (4.8)
                  [((T picks up chanter))
24: T: B_<*grip>C_B_<*grip>[C_<G>B_[<grip>C_____((note held))
                           [((S nods))
                                   [((T nods while playing correct
                                     grip))
T looks at S.

25. T: instead of getting in the grip [movement (3.5)
    T: _______________________________[B_<grip>C_____(0.8)_ _ _ _

T plays short extra phrase then mutes chanter.

26. T: right? now (1.4)

T and S both look towards screen.

27. T: [like if we played that one, that would be a good one (0.2)
       [((T raises right hand to point at screen))
28. T: 'cos you've got two (0.4) even (0.4) low Gs there (0.6)
29. T: right and that's the way they should be (0.4)
```

```
30. T: [see how this one's (2.0) different (0.4)
       [((T looks and points at a different position on screen))
31. S: yeah (0.5)
32. T: right? (0.7)
33. T: so you've got to get that- th- the low Gs should be the
       same
```

Transcript 6.9: T demonstrates good and bad *grips* using both the chanter and the performance display.

It is notable that T does not use the ornament recognition/evaluation facility at any point during this excerpt, neither to detect the error in the first instance, nor in the subsequent process of analysing S' technique. As a highly experienced piper and professional instructor, it is likely that T is more confident in his own ability to evaluate the performance of the embellishment than that of the system. However, having initially identified the mistake in the traditional manner (i.e. aurally, during playback), T does use the display to provide visual evidence in support of his observation. This suggests that while T is undoubtedly the authority in terms of ornamentation technique, the availability of additional means with which to describe his feedback to S can be beneficial in the lesson context.

6.4.4 Case Study 4: Error Identified from Performance Display

This example, which took place in the final week of the study, illustrates the extent to which T became able to interpret the information provided by the system. After initially activating the error detection facility which highlighted a supposed false fingering, T realises that it is actually a D gracenote which has exceeded the duration threshold for the ornament detection algorithm. However, following further examination of the relevant passage in the display, T becomes aware that the embellishments played by S are somewhat different to the intended ornamentation for the tune. T is sufficiently familiar with the performance display notation by this point in the study that he is able to sight-read the passage as played by S from the screen, allowing him to demonstrate both the correct and incorrect ornamentation of the phrase.

Figure 6.9 depicts the GUI as it appeared in the lesson. The apparent false fingering error can be seen in bar 9. Transcript 6.10 shows T examining this error, beginning with T and S both looking at the screen.

Figure 6.9: Performance display from Case Study 4. The apparent false fingering can be seen in bar 9.

1. T: let's just click on [that (2.6)
                          [((T clicks the mouse button))

T clicks on highlighted note to bring up text window.

2. S: so ((reads from screen)) C hole is covered=
3. T: =I think it's a D gracenote you've just played (0.6)
4. T: [but it's just- it was- [it's just- it's just big (0.4)
      [((T looks at S))
                              [((T mimes D gracenote with right
                                hand))
5. T: you know s- so it's [classing it as a note
                          [((T looks at screen))
6. T: instead of a- a [gracenote (12.2)
                      [((T mimes D gracenote with right hand))

Transcript 6.10: T realises the false fingering detected by the system is actually a gracenote which exceeded the ornament detection duration threshold.

T studies the screen for a further 12 seconds while making small movements in the air with the fingers of his right hand. These finger gestures appear to be D gracenotes and *bow* ornaments. T then explains to S that he has been performing the wrong embellishments for this phrase, and demonstrates both the correct and incorrect ornamentation (notation for which is provided in Figure 6.10(a) and (b) respectively). Transcript 6.11 begins with T describing this feedback to S.

```
7. T: see [I think that’s (1.7)
          [((T points to screen))
8. T: [going
      [((T picks up digital chanter))
9. T: <dbl>B_<bow>lA_B_<bow>lA_<D>B_[<bow>lA_
                                     [((T looks at S))
10. T: [I think you’re putting D gracenotes (6.3)
    T: [<D>B_<bow>lA_<D>B_<bow>lA_<D>B_<bow>lA_<D>B_<bow>lA_
```

T looks towards the screen.

```
11. T: <dbl>B_<bow>lA_<D>B_<bow>A_
12. T: yeah, so s- (1.0)
```

T removes fingers from chanter holes to mute sound.

```
13. T: th- the [actual- the actual music [for it goes (1.4)
               [((T raises right hand to point at the screen))
                                         [((T puts fingers back
                                           on chanter))
14. T: <dbl>B_[<dbl>B____(0.8)
    T:        [B doud- B- B doubling (0.8)

15: T: ((sings)) "bow B [bow" (0.7)
    T: ______ <bow>lA_B_[<bow>lA____((note held))
                        [((T looks at S))
```

T looks towards screen.

```
16. T: and on there you’re going ((sings))
17. T: "B doubling" (2.4) [gracenote to A (1.8)
    T: <dbl>B_______(2.4) [<G>lA_____((note held))
18. T: D gracenote and then doing a [bow (0.9)
    T: ________________________<D>B_[<bow>lA_____((note held))
```

T looks at S.

```
19. T: so you’re putting in a lot more than’s asked (0.1)
```

(a) (b)

Figure 6.10: (a) Correct ornamentation for phrase and (b) incorrect ornamentation performed by S in Case Study 4.

```
20. T: ((sings)) ["B doubling bow B bow"
    T: __________[<dbl>B_<bow>lA_B_<bow>lA____((note held))

21. T: that's what you've got to do (0.2) and you're going (3.2)
22. T: <dbl>B_<G>lA<D>B_<bow>lA____((note held))
```

Transcript 6.11: T demonstrates both correct and incorrect ornamentation of the phrase while singing and speaking along.

S then attempts to perform the phrase, but plays the same incorrect embellishments. T joins in and they play the phrase correctly together. This is shown in Transcript 6.12.

```
23. T: you're putting a few extra grace=
24. S: =<dbl>B_<G>lA_[B_<bow>lA____((note held))
25. T:                [nope (0.7)
                      [((T points to S' hands))
26. T: there (0.2) [so y- it's just the two- it's two bows (0.3)
                   [((T picks up chanter))

27. T: ((sings)) ["tada bow B bow" (0.5)
    T:           [<dbl>B_<bow>lA_B_<bow>lA__(0.5)
28. S: __________[<dbl>B_<bow>lA_B_<bow>lA_(0.3)

29. T: [((sings)) ["B doubling bow B bow" (0.6)
       [((S mutes chanter))
    T: ___________[<dbl>B_<bow>lA_B_<bow>lA_____(0.9)
30. T: right so if you can get that coming through
```

Transcript 6.12: S plays the wrong ornamentation again, T joins in.

The performance being examined in this case study was recorded by T and S simultaneously. Although playing together is valuable for identifying synchronisation and timing problems (several of which had been previously pointed out by T following the recording), it can cause subtle but important mistakes such as this example of incorrect ornamentation to be difficult to discern, even for an experienced tutor. The system allows such errors to be uncovered in the recorded performance, either using the playback facility, or as in this case, directly from the visualisation. It is an encouraging observation that the tutor (who in the first week of the study had volunteered *"I'm no great on a computer... they scare me"*) quickly became adept in both the operation of the system and interpretation of the display.

6.5 Lesson Study: Discussion

6.5.1 Affordances of Digital Chanter System

The video recordings of the lessons illustrate several advantages, both deliberate and accidental, provided by the system compared to a traditional practice chanter. The ability to capture student performances and provide flexible and multi-modal means of examination is the primary affordance inherent in the design of the system. In particular, as an advocate of critical listening, the tutor regularly used the playback facility to encourage students to reflect on their own playing. While the benefits of self-reflection using simple audio recording are well established (Klickstein, 2009), the capacity to store performances in a symbolic representation provides several advantages in terms of flexibility, such as adjusting playback speed, listening to simultaneously recorded performances either together or separately, and straightforward navigation to a desired point in a recording. Participants were regularly observed to study the visual performance display during playback, which often led to the identification of subtle errors that had not previously been detected (as illustrated in Section 6.4.3).

Table 6.5 shows that a greater number of fingering errors were identified in the test group than the control group, the majority of which were detected using the GUI display. This implies that the false fingering detection facility was found to be a useful tool in detecting fingering errors which could otherwise pass unnoticed, an assertion supported by frequent comments from the instructor over the course of the study. Moreover, the fact that the tutor began to recognise a greater number of false fingerings in the control group lessons after having used the GUI for several weeks (Table 6.6) suggests that using the system may have increased his awareness of the students' propensity to false-finger certain notes even when the automated feedback is absent.

One unintentional affordance of the digital chanter itself is that it enables the user to speak or sing whilst playing. This was regularly exploited by both tutor and students (as seen in several of the case studies in Section 6.4), and allowed the instructor to explain an error or technique while simultaneously demonstrating the fingering and resulting sound. Moreover, it was observed frequently and by several participants that the sound produced by the system is considerably less "forgiving" than that of an acoustic GHB or practice chanter, such that crossing noises and ornamentation errors are significantly more audible when performed on the digital interface.

6.5.2 Secondary Effects of System in Lesson Context

6.5.2.1 Identification of Ornament Errors

One result from Table 6.5 which could be interpreted as a detrimental effect of the GUI system is the observation that far fewer instances of ornamentation errors were identified in the test group than in the control group. This can perhaps be at least partially explained by the amount of time spent playing simultaneously (tutor and student together) versus individually. Synchronous performance accounts for 53% of the total playing time in test group lessons, compared to only 23% in the control group (Table 6.9). It is likely that subtle mistakes such as inaccurate ornamentation are more difficult to detect when playing together (as opposed to e.g. timing errors, which were identified more often in the test group).

Furthermore, while the instructor would often remain silent and allow students to correct themselves in the event of mistakes in the melody or timing during control group lessons, he tended to highlight ornament errors immediately. In such cases, the student sometimes continued playing (in which case the instructor's feedback was often as little as a pointing gesture and the word "no"), while at other times the tutor signalled the pupil to stop in order for the error to be explained (causing the performance to be broken into short sections).

However, the fact that recorded performances were significantly longer on average (63s) than playing instances in the control group (32s) suggests that the instructor was less inclined to interrupt while students were using the test group system. This may be because the performances would be available to examine in their entirety upon completion of the recording, and hence small errors need not be pointed out immediately to prevent their being forgotten. In this way the system functions as an extended memory for the instructor, allowing him to prioritise which mistakes most require his attention after the student has finished the tune. This would at least partially account for the reduced number of ornament errors which are identified during performance but for which little or no explanation is provided.

6.5.2.2 Effect on Individual and Synchronous Playing Behaviour

The increased percentage of simultaneous playing in test group lessons (Table 6.9) appears to be a significant effect of the use of the digital chanter system. Instances of tutor and student playing together are comparatively infrequent in the control group, which is aligned with the findings of (Duffy & Healey, 2012) that synchronous activity accounts for a relatively small proportion of instrumental instruction. It could be argued that this represents a shortcoming of the system, in that it affects a fundamental aspect of traditional tuition. It is possible that the tutor conducted the test group lessons in this way out of some sense of obligation; that is, he was aware that the purpose of the study was to evaluate the system, and so determined to use it as often as possible. Equally, the "new toy factor" could be partially responsible for the difference in playing behaviour; the effect might gradually decrease if the system were to be used over a longer period of time as the novelty wears off.

However, the fact that the percentage of synchronous playing in test group lessons increased steadily from 44.9% to 65% over the duration of the study (Table 6.9) could be seen to suggest that the change in playing behaviour is a deliberate decision, and that with increasing familiarity with the operation of the system, the tutor found this to be the most effective use for the technology. If the tendency towards individual playing in the control group is due to the difficulty of identifying subtle but important errors (such as poorly executed embellishments) when playing together, the system would remove this necessity, allowing pupil and teacher to focus on temporal accuracy while playing, then examine technical mistakes using the playback and display functions afterwards.

It should also be noted that the facility to record two digital chanters simultaneously was specifically suggested by the instructor during the pilot study discussed in Section 5.3, as he felt this would provide a more meaningful measure of timing deviations between performances than the original prototype, which could only record individually. With this in mind, it is perhaps unsurprising that the instructor chose to use the system in this way.

Another statistic which might imply a negative effect of the system is the fact that less of the overall lesson time is spent playing in the test group (40%) than the control group (58%), as shown in Table 6.8. This can be accounted for by the time devoted to examining performances using the GUI in the test group (21%), of which around one third was occupied by performance playback (7%). Table 6.7 shows that errors found using the GUI are discussed for longer on average than those identified by the instructor without using the system. This may be partially due to the time expended interacting with the GUI controls, which could be seen as wasted time compared to the control group. However, the relative ease with which the tutor became adept in the operation of the system suggests that this was not the primary reason, at least in the later weeks.

Nonetheless, it is evident from the case studies (for example, lines 6-9 in Section 6.4.4) that the instructor sometimes spent a considerable amount of time looking at the display before providing his feedback. While it is true that no useful information is being communicated to the pupil during such periods, the time is not being wasted; in instances where the system has identified an error which had not previously been noticed, it is inevitable that the tutor must familiarise himself with the details of the mistake before interpreting and explaining it to the student.

6.5.2.3 Potential Distracting Effect of Technology in Lesson Environment

Perhaps surprisingly, the amount of time the participants spent talking about the system itself (e.g. discussing the sound and physical feel of the chanters, and making suggestions for additional features, as opposed to referencing specific GUI feedback) was approximately the same between the test and control groups (around 8%). However, this took place almost entirely within the first 3 weeks of the study, which suggests that while the technology may have initially had a distracting effect in both groups, this would not persist if the system were to become a permanent addition to the lesson environment.

6.5.3 Student Perspectives

The analysis of the sessions conducted during this study has focussed primarily on how the instructor used the system, and on quantifiable behaviours such as playing duration and instances of error identification. One consideration which can not be easily measured in this way, but which is nonetheless central to the overall aim of supporting the learning process, is the effect of the system on the lesson environment from the perspective of the students.

In broad terms, the survey results suggest that the digital chanter itself was well received; both test and control groups provided the same positive responses to the statements "I found the digital chanter was fun to use" (4.6/5) and "I think the system would be useful as a practice tool" (4.8/5). However, the possibility that the pupils may have felt compelled to answer in this way so as not to displease either the instructor or the researcher cannot be discounted (despite efforts having been taken to minimise this effect by stressing the importance of constructive feedback and anonymising the responses).

The main motivation for the participant surveys was to examine the students' perception of their own awareness of errors in their playing. While the overall results presented in Section 6.3.3 suggest little or no statistical significance, one potentially relevant observation on this subject concerns the Likert statement "I believe that if I ever do make crossing noises, I am always aware of it". This was the only question for which the unpaired t-tests between the before/after differences in the two experimental groups (Table 6.12) rejected the null hypothesis ($p < 0.05$). Table 6.10 shows that the mean response to this statement for the control group students increased by 0.5 between the beginning and end of the study. This could be due to the sound produced by the digital chanter being less "forgiving" than an acoustic chanter and thus accentuating the presence of crossing noises, as was frequently stated by both the instructor and several students during the sessions.

Conversely, the test group students reported a decrease of 0.8 with regard to awareness of crossing noises. This may be caused by the error detection algorithm highlighting very short intermediate states between notes as mistakes, which tends to lead to multiple error annotations appearing on every recording whenever the "Display Errors" button is activated. This behaviour was a deliberate design decision, the rationale being that the user could gain insight from these annotations, and would be able to use the playback function to interpret which constitute serious mistakes. Nonetheless, it is possible that by pointing out too many supposed errors which do not correspond to audible crossing noises, the student's confidence in their own ability to detect these mistakes could be undermined.

A more nuanced understanding of the students' awareness of errors might be obtained by examining the video footage of the lessons with regard to, for example, changes in facial expression when a mistake occurs. However, this would incur significant subjective judgement on the part of the researcher as to what constitutes an error in a given context (the results discussed above concern only those mistakes which are explicitly identified by the tutor). Such an approach would also be unlikely to provide meaningful results in terms of comparison between participants, though may well prove to be illuminating on an individual case study level.

6.5.4 Reflections on System “Roles” in Lesson Environment

The participants were observed to interact with the system in a variety of different ways during the sessions, as illustrated by the case studies described in Section 6.4. Put another way, the system could be said to fulfil several “roles” within the lesson environment depending on the situation. In the first case study (Section 6.4.1), the instructor uses the GUI feedback to describe a false fingering which he had identified while the student was recording the performance. Given that the tutor was already aware of the mistake, the decision to bring up the fingering analysis text window might at first seem somewhat redundant. However, a contrasting interpretation would be that the system is here accorded the role of impartial arbitrator, providing objective evidence which the instructor can use to corroborate his observations to the pupil.

In Section 6.4.2 the tutor employed the system not only to uncover an error which had gone unnoticed during the performance, but also to interrupt the student’s attempt to talk over him and change the subject. At other times the system was used as a vehicle for self-reflection (the tutor would instruct the pupil to listen critically to his/her recording), an extended memory for the instructor (Section 6.5.2.1), an analysis tool for joint exploration and comparison of multiple recorded performances using the visual display, and a yardstick for setting performance goals (*“try it again and see if you can get fewer red bits”*).

The fourth case study (Section 6.4.4) demonstrates an interesting point regarding the error detection facilities: the system can be “wrong” and still be useful. The instructor realises that a note which has been detected as a false fingering was in fact intended to be a D gracenote. This immediately implies that the gracenote was too long (which may or may not be a problem with a student’s playing depending on their level of experience). However, on closer inspection of the passage using the display, the tutor identifies a far more serious error, i.e.

that there should not be a D gracenote in this phrase at all. This observation illustrates a significant consideration for the design of “intelligent” systems of this kind; it is important to ensure that the data is presented in such a way as to be interpretable by an expert, so that even when the system “fails”, some meaningful information can still be derived by the user.

6.5.5 Limitations of Study

The main limitation of this study is the reliance on only one instructor. This was primarily due to practical constraints; the chance to work with a tutor who has such extensive piping and teaching experience, such a large number of pupils, and who was prepared to use the system in his lessons over an extended period of time was a rare opportunity. Without repeating the process with several more teachers, it is not possible to say with any certainty whether the results observed during this study would extend to the general case. Instead, this work presents a series of specific observations on the effects of introducing the technology into a particular lesson context, and relies on the eminent expertise of the instructor to accord any potential significance to the outcomes.

An unexpected technical limitation of the system prevented the sensor measurements from the digital chanters being logged other than when performances were deliberately recorded by the instructor. While this data would theoretically have allowed some automated investigation of the actual number of errors present against those identified by the instructor, in practice this would likely have been extremely time consuming, as significant pre-processing would be required to distinguish true errors from, for example, sensor noise produced when handling the chanter. In any case, the number of errors pointed out by the tutor is a far more useful figure; he often chooses to ignore certain mistakes which are quite obvious when watching the video recordings, such that any comparison against an automatically generated error tally would be unlikely to provide a meaningful result.

6.6 Solo Practice Study

This section describes a focussed user study which was carried out to investigate how the digital chanter system could be employed in the context of solo practice. Four adult male pipers (referred to hereafter as P1, P2, P3 and P4) took part separately on different days; there was no contact between participants. The playing experience of the participants was as follows: P1 = 19 years, P2 = 36 years, P3 = 6 years, P4 = 23 years.

6.6.1 Procedure

Prior to the study, participants were aware that the purpose of the exercise was to investigate the use of a digital bagpipe chanter system as a tool for solo practice, but were not familiar with the details of the system (e.g. the ornament and error detection facilities). Each participant was asked to use the system during three practice sessions of 30-60 minutes on consecutive days. In each case, the author was present during the first practice session to provide assistance and answer any questions relating to the operation of the system. The procedure for this first session with each participant was as follows:

1. The researcher (R) demonstrated how to play the digital chanter hardware, without making any reference to the software.
2. The participant (P) was given the digital chanter to play for a few minutes, in order to become familiar with the physical interface.
3. P was asked to identify two tunes which would form the basis of their practice over the course of the study. The criteria for selection were (a) tunes that P was currently practicing/learning, and (b) tunes that are examples of traditional repertoire (e.g. marches, strathspeys or traditional reels, rather than modern style tunes).
4. Before explaining the operation of the software, P was asked to perform both tunes along to a metronome. These performances were recorded by R using the system.
5. The operation of the system was then explained to P in the following order:
    (a) Opening new and existing sessions.
    (b) Connecting chanter hardware.
    (c) Chanter hardware controls (pressure sensor on/off, “reed strength”, record enable).
    (d) Recording a performance.
    (e) Basic performance display controls (zoom in/out, bar lines on/off, show/hide performance).

Participant	P1	P2	P3	P4
No. years piping experience	19	36	6	23
No. days with system	4	3	5	3
Approx. time spent using system (hrs)	2:55	3:00	10:15	2:50
No. performances recorded	23	21	30	19
No. instances playback facility used	38	30	89*	18
No. instances ornament detection used	22	14	3*	8
No. instances ornament analysis used	18	26	3*	13
No. instances fingering analysis used	70	40	16*	12

Table 6.13: System usage by each participant in solo practice study (*incomplete data: approximately 2:55 hours of log files missing).

(f) Playback facilities (start/pause/stop, select start point using GUI, metronome on/off/volume).

(g) Ornament detection and ornament error feedback facilities (demonstrated on performance recorded by R).

(h) Fingering error detection facilities (demonstrated on performance recorded by R).

6. P was then asked to practice the two tunes for 15-30 minutes each using the system. R was present to answer any questions regarding the operation of the system, but did not actively participant in the practice session.

Following this first session, participants were asked to describe any initial thoughts on the experience of using the system. Each participant then took the digital chanter system home to use for a further two practice sessions over the following days. The system stored all performances recorded by the user, and was also configured to log the raw data from the chanter, plus all GUI interaction (i.e. which button was clicked, and when). At the conclusion of the study, participants were asked to record the same two tunes that were recorded in the introductory session. Participants were then given the opportunity to provide further thoughts and comments about the system in the form of a semi-structured interview, and a Likert-style questionnaire (provided in Appendix D).

6.6.2 Results

6.6.2.1 System Usage Logs

Table 6.13 shows how often the various system features were used by each participant. For clarity, “ornament detection” refers to the participant activating the “Display Ornaments” button to highlight all of the embellishments on the display, while “ornament analysis” means that the text window feedback for a particular ornament was consulted. All participants used the system for approximately 3 hours, with the exception of participant 3 who spent more than 10 hours using the digital chanter over 5 days. When the system was returned by P3, approximately 2:55 hours of GUI log files were found to be missing, the cause of which remains unclear. For this reason, the instances of GUI feature usage reported in Table 6.13 only concern the remaining 7:20 hours of log file data. The chanter log files and performance recordings for this period were unaffected.

The results displayed in the table indicate that each participant used the system differently according to their own requirements and/or preferences. For example, while P3 used the recording and playback facilities significantly more often that the other participants (which is perhaps unsurprising given the greater length of time spent with the system), he consulted the ornament analysis feature only 3 times (the least of any participant), and employed the false fingering detection far less frequently than P1 and P2.

6.6.2.2 Participant Survey Responses

Table 6.14 shows the mean responses to the 11 Likert-style survey statements across all four participants. Each statement was rated between 1 and 5; for questions relating to how often a particular feature was used, this corresponds to the answers “never” (1) to “very frequently” (5). For statements of the form “I found [feature x] useful”, the responses range from “strongly disagree” (1) to “strongly agree” (5).

All four participants agreed strongly that the playback facility was useful, and only one participant (P1) reported the slightly lower result (4 = “agree”) regarding the usefulness of the visualisation/display feature. The ornamentation, crossing noise and false fingering features all attained a mean result of at least 4, though there was greater variation between individual responses according to

Likert statement	Mean response
I used the performance visualisation/display facility:	4.25 / 5
I found the performance visualisation/display facility useful.	4.75 / 5
I used the performance playback facility:	4.25 / 5
I found the performance playback facility useful.	5 / 5
I used the ornament detection/feedback facility:	4 / 5
I found the ornament detection/feedback facility useful.	4 / 5
I used the "Display Errors" facility:	4 / 5
I found the false fingering detection useful.	4.25 / 5
I found the crossing noise detection useful.	4 / 5
I used the air pressure sensor facility:	2 / 5
I found the air pressure sensor facility useful.	3.67 / 5

Table 6.14: Mean participant responses to survey questions in solo practice study.

the participants' preferences.

The survey responses indicate that the pressure sensor was rarely used during the study. This is confirmed by the system logs, which show that two of the participants (P2 and P4) did not use the facility at all, while P1 and P3 only used it briefly on one or two occasions. However, participants did suggest that the feature would be useful for certain situations, both in the survey and in the interviews. For example, P1 stated that he did not use the air pressure facility extensively since he was currently living in a rural area, and was thus able to practice with an acoustic GHB regularly, but had he still been resident at his previous address in central London he would *"definitely"* have found the pressure sensor to be a valuable feature.

6.6.2.3 Numerical Analysis of Before and After Recordings

Each participant recorded two tunes of their own choosing prior to the first session, and then again at the end of the study. The resulting recordings were analysed using the ornament and error detection algorithms to investigate whether any changes in the players' technique could be identified after several days of practice using the system.

It should be noted that for the purposes of the automatic analysis, false fingering errors are only counted above a certain duration threshold. This is because a very brief false fingering (e.g. lifting the bottom hand fractionally early when

Error/technique	Tune 1		Tune 2	
	Before	After	Before	After
Ornament Errors	15	11	23	25
False Fingerings	6	5	2	0
Crossing Noises	15	7	79	67

Table 6.15: Numerical analysis of before and after recordings for participant 1.

Error/technique	Tune 1		Tune 2	
	Before	After	Before	After
Ornament Errors	54	50	28	22
False Fingerings	6	11	12	12
Crossing Noises	27	33	84	63

Table 6.16: Numerical analysis of before and after recordings for participant 2.

moving from High A to D) can in some instances be acceptable in order to avoid an audible crossing noise. Therefore, while it is beneficial for the GUI system to identify incorrect fingerings of any length when providing feedback to the player, the errors reported in this section refer to false fingerings of duration $L \geq 85$ms. This is the same empirically determined value used in (D. W. H. Menzies & McPherson, 2012) to distinguish potential ornaments from melody notes, which implies that any incorrect fingering longer than this threshold can be said to span a significant portion of the note in question.

Table 6.15 shows the results obtained for the before and after recordings by P1. This participant employed the fingering analysis feature significantly more than any other user (Table 6.13), and described this as *"the most useful"* aspect of the system during the interview. For both tunes, an improvement can be observed for false fingerings and crossing noises. This suggests that P1's frequent use of the fingering analysis tool may have had a positive effect on his technique, or at least increased his awareness of certain errors in his playing.

Moreover, P1 achieved fewer ornament errors in Tune 1, although Tune 2 exhibits a slight increase in this category. In the interview, P1 reported having found the ornament detection less helpful than the fingering analysis, and rated its usefulness at only 2/5 in the survey. Conversely, P2 (who provided a score of 5/5 for the same Likert statement) achieved a reduced number of embellishment errors for both tunes (Table 6.16).

Error/technique	Tune 1		Tune 2	
	Before	After	Before	After
Ornament Errors	40	46	19	18
False Fingerings	0	1	0	1
Crossing Noises	27	34	29	33

Table 6.17: Numerical analysis of before and after recordings for participant 3.

Error/technique	Tune 1		Tune 2	
	Before	After	Before	After
Ornament Errors	33	39	7	8
False Fingerings	7	3	3	3
Crossing Noises	46	44	26	19

Table 6.18: Numerical analysis of before and after recordings for participant 4.

P2 also attained a significant improvement in crossing noises for Tune 2 (with no change in the false fingering category). However, in Tune 1 both false fingerings and crossing noises were found to increase. This may be due to P2's decision to record the tune 5bpm faster than the previous attempt (P2 reported being unhappy with the original tempo, though admitted after the recording *"that's the fastest I've ever played it"*).

Tables 6.17 and 6.18 illustrate the results for P3 and P4 respectively. P4, a highly experienced player, achieved a reduction in crossing noises for both tunes, and in false fingerings for Tune 1 (no change in Tune 2), though ornamentation errors were shown to increase slightly. Meanwhile, the recordings for P3 (who rarely used the fingering and ornament analysis tools despite playing the digital chanter for more than 10 hours over 5 days) demonstrate an increased number of errors in every category, with the exception of a modest improvement for ornamentation in Tune 2.

Rather than use the GUI feedback, P3 generally employed the playback function to examine recorded performances, as shown in Table 6.13. This could provide some explanation as to the increase in fingering errors; the digital chanter system makes no sonic distinction between correct and incorrect fingerings. The addition of some aural feedback to emphasise false fingerings might therefore prove valuable to users wishing to practice without consulting the GUI analysis tools.

Moreover, while a true "crossing noise" is by definition an audible mistake, subsequent examination of P3's recordings revealed that many of the reported errors were too short to be heard clearly at full playback speed, and would almost certainly be inaudible on an acoustic GHB. This might imply that the crossing noise detection threshold should be relaxed so as to highlight only those errors that would produce a noticeable sound. However, the fact that the other participants (with the exception of Tune 1 by P2 as discussed above) were all successful in reducing the number of crossing noises identified suggests that the current hyper-critical approach may indeed be effective.

6.6.3 Discussion of Interview Responses

6.6.3.1 Participant Usage Patterns and Perceived Benefits

The semi-structured interviews conducted with each participant upon finishing the study provide further insight into the different ways in which the system was incorporated into their solo practice. P1 reported that he began by recording each tune several times, and identifying recurring mistakes using the error detection facilities. He then focussed on these sections, recording repeated performances of the relevant passages in isolation. Interestingly, when making these recordings, P1 first exaggerated the mistake several times before attempting to execute the phrase correctly. While the merits of deliberately performing errors are perhaps questionable as regards the development of muscle memory for good technique, it seems that this approach reinforced P1's trust in the system feedback (i.e. that the highlighted errors were indeed present in his original performance).

An example of an error which was identified and practiced by P1 in this way can be seen in Figure 6.11, which shows the recording of Tune 2 ("Cock O' The North") made prior to commencing the study. The red notes in bars 6 and 14 denote a false fingering when changing between High A and C. This mistake was not present in the performance recorded after the study, which suggests that the system helped P1 to improve his execution of this movement.

P2 also began by recording performances and using the detection facilities to highlight mistakes in fingering and ornamentation. He then used the GUI to navigate and listen to the sections where errors were identified:

> *"I didn't necessarily listen to the whole tune back; what did interest me was to look at the display of the ornaments and to display the*

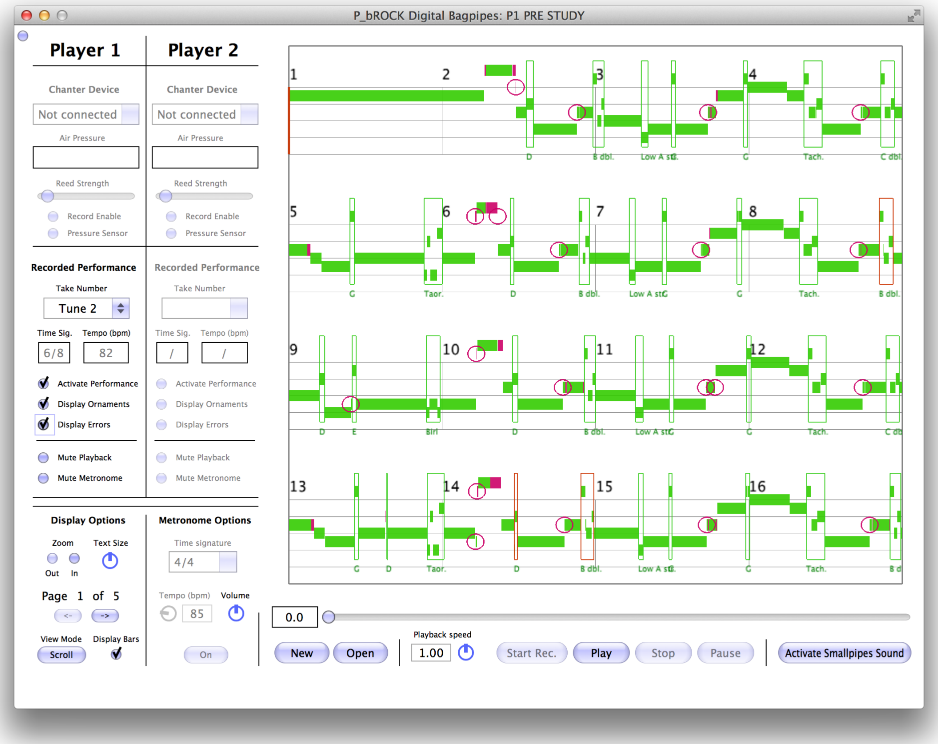


Figure 6.11: False fingering errors in performance by participant 1 prior to commencing the study.

> *errors on the screen, because then I could play certain sections [. . .] and I could then just focus on those areas."*

In particular, P2 described the display as being useful for recognising not only individual errors, but also repeated mistakes in passages which occur multiple times throughout a piece:

> *"You can look at a tune in its entirety, and you can see patterns of where things are coming up [. . .] there's phrases that come up all the way through certain tunes, and you can see it quite clearly there's a red bit there, and immediately underneath it."*

P3 reported using the system *"instead of a practice chanter"*. While he did not make frequent use of the ornamentation and error detection tools, he employed the recording and playback facilities regularly. When asked which features he had found most useful, he replied:

> *"The visual aspect, so you can see what notes you're playing and when, and for how long, even the gracenotes, you can tell how long you're playing the different gracenotes."*

P3 made several references to the benefits of the performance display for examining deviations in timing; for example, in the context of ensemble playing:

> *"It's good for band environments as well as solo, that's the good thing, because you can tell if someone's speeding up or slowing down."*

Moreover, the system logs indicate that P3 often used the system to record both melody and harmony parts for a tune and listen to them together. He reported having found the display facility useful for comparing phrasing between such performances (*"you can tell how close you are with each note"*).

P4 also used the display to overlay multiple recordings in order to provide a visual comparison of rhythmic features, which he described as follows:

> *"It's fascinating seeing just how far out some of the things you play are; bits of it are just about perfect, and other bits are horrible."*

As a professional piping instructor, P4 reported not having used the system features to analyse his own playing as much as he would do with students:

> *"What I did do was I actually spent quite a lot of time just using it as an instrument [...] so I probably didn't use the system to its fullest extent. I can definitely see how I would use it as a teaching tool with pupils, and especially for their own practice at home, I think this would be a brilliant thing for people to have at home, to be able to play a tune and actually see how it's differing from my interpretation."*

Discussing the importance of self-evaluation during solo practice, P4 stressed the benefits of having a device to facilitate recording and playback with minimal effort. Furthermore, even in instances where the system is either incorrect or overzealous in its detection of errors, this can be seen as an opportunity for critical reflection rather than something to be ignored or trusted without consideration:

> *"One of the simplest things you can do is just record yourself, but I've got a recorder set up through there and I never do it, or I record myself and never listen [...] so having something like this that just turns round and says 'no, no, no, no', you know, even if you don't agree with all of them, it makes you question yourself."*

6.6.3.2 Suggested Improvements

The study participants identified several aspects of the system that they felt could be improved or enhanced. Speaking as an instructor, P4 suggested adding different "feature levels" to the GUI which could be selected based on the user's level of experience:

> *"The system as it stands, I wouldnt give that to someone who's been playing 2, 3, 4 weeks, there's way too much there. [At] that kind of stage all we're focussing on is the mechanics of the fingers."*

To illustrate this point, P4 proposed that for very early stage players, a suitable GUI would simply show the current note being played and whether or not the fingering is correct. More advanced features such as ornamentation and air pressure displays could be added as the user's technique progresses.

P4 also felt that the addition of some programmed learning (e.g. in the form of scored exercise drills) would be *"an obvious extension"*, and stated that *"you could even build an entire tutorial in the software"*. Moreover, P4 suggested the addition of both a "karaoke mode" and a game interface to provide performance scoring. It should be noted that all of these comments were made with no knowledge of the existence of the *Bagpipe Hero* interface. Following the conclusion of the study P4 was then introduced to *Bagpipe Hero*, which he described thus:

> *"That is absolutely brilliant. Doing something like that at the end of a band practice or something [...] that's fantastic."*

Other proposed improvements included the option to specify a range of bars in the GUI display rather than relying solely on the zoom tools; a practice chanter mouthpiece and rubberised sole to increase stability; and moving the USB socket from the bottom of the chanter to the side so as to avoid putting unnecessary pressure on the connection.

Another pedagogical application not directly related to performance was proposed by P3: a "tuning tutor" facility. Many pipers use black insulation tape to tune individual notes on an acoustic chanter by partially covering the holes. P3 suggested that the continuous sensors on the digital chanter could be used to develop an interface to help inexperienced player to learn and practice this skill, providing advice as to which hole(s) should be adjusted (and by how much) in order to achieve the desired pitch.

6.7 *Bagpipe Hero* Evaluation

This section describes a limited evaluation of the *Bagpipe Hero* program. While a longitudinal analysis of user engagement is beyond the scope of this study, players are unlikely to find the game useful or enjoyable if the scores provided do not appear to reward good technique and accurate performance of the tune (Richter et al., 2015). The purpose of this study is therefore to investigate the extent to which the scores generated by the system are aligned with the opinions of human listeners in terms of performance quality.

6.7.1 Procedure

Following the main lesson study described in Sections 6.2 to 6.5, a short session was conducted in which the instructor and three senior pupils at the school took turns to perform three tunes on *Bagpipe Hero* (with the exception of the tutor, who only played two of the pieces). The students all had a similar level of playing experience (approximately 4-5 years), while the instructor is a professional piper of 30 years. The session was video recorded, and all of the players' performances were stored by the system.

After the session, the resulting performances were anonymised and saved as audio files, along with the template recording for each piece. These audio files were used to create a web-based listening test, in which participants were invited to provide percentage scores for the individual performances. The three tunes constitute three separate pages of the online survey, the order of which is randomised for every listener. Each page presents the template recording (labelled "Exemplar") and the 3-4 user performances in separate audio players. For each tune, the players' recordings were named R_1 to R_4 by a random number generator to minimise any bias arising from the order in which they are heard by the listener.

The first page of the listening test provides some introductory information about the study, and basic instructions for how to rate the performances, as given below:

> *Thank you for agreeing to participate in this research. The purpose of this survey is to gather opinions from experienced Highland bagpipers, in order to assess the quality of multiple performances of 3 well known pipe tunes. All of the performances were recorded using the same electronic bagpipe chanter.*
>
> *For each tune, you will be provided with 4 or 5 short audio samples: an exemplar/ideal recording of the piece, and 3 or 4 different performances recorded by different people. You can listen to each recording as many times as you wish, but please listen to both the exemplar recording and all performances at least once in full.*

> *For each performance of the tune, you will be asked to provide a score out of 100. Please try to base your score on the quality of the performance as a whole, across its entire length (taking into account concepts such as timing, ornamentation/embellishments, crossing noises and accuracy of the melody). Please note that you are being asked to rate the quality of the players' performances, not the audio quality of the bagpipe sound.*

Participants were also asked to provide their age and number of years of piping experience prior to commencing the listening test. The link to the survey was shared online via the Scottish Piping Society of London[2]. The resulting responses are presented in the following section.

6.7.2 Results and Discussion

In total, 12 pipers responded to the survey. The ages and experience levels of the participants span a broad range, and are shown in Table 6.19. Five listeners completed the entire test, while seven exited the survey after completing the task for either one or two tunes. Since the order in which tunes were presented was randomised, the total number of responses for each tune is as follows: Tune 1 = 9 responses; Tune 2 = 8 responses; Tune 3 = 6 responses.

Table 6.20 shows the means of the percentage scores provided for each recording (R_n) of the three tunes, along with the score allocated by the *Bagpipe Hero* system. Mean scores are calculated both for the five listeners who completed the entire test (for consistency between tunes), and for all participants responses (to provide the maximum number of data points); these categories are labelled S_C and S_A respectively. The ranked order of these scores is shown in Table 6.21.

The results from Table 6.20 are shown in graphical format in Figure 6.12. From these plots, two observations can be made. Firstly, the scores provided by human listeners are significantly lower than those generated by the system, by approximately 30% on average. This may be due to the fact that listeners were not given any indication that the majority of the recordings were made by young and relatively inexperienced players, and hence did not take this into consideration when grading the performances. In this case, the absolute difference between human and computer-generated scores is not perceived to be a negative reflection of the operation of the system; in order to foster motivation among students, it

[2] `http://www.scottishpipingsocietyoflondon.co.uk`

Age Group	**Number of Participants**
Less than 18	1
18-29	3
30-39	2
40-49	2
50-59	2
60+	2

Years of Experience	**Number of Participants**
0-3	0
3-5	1
5-10	3
10-15	1
15-20	0
20+	7

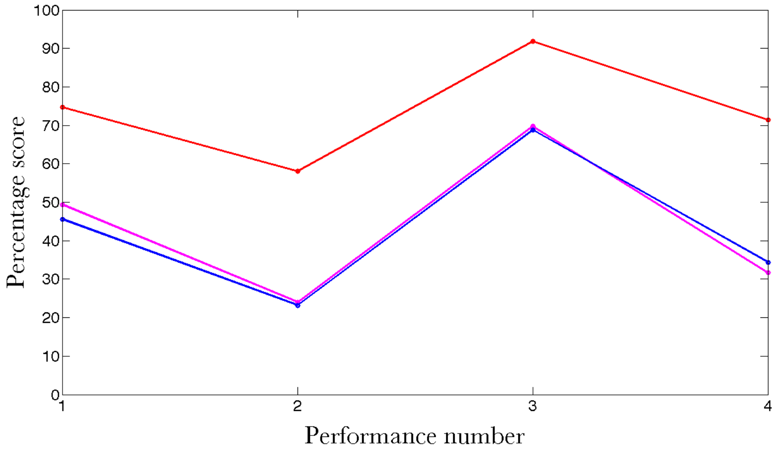
Table 6.19: Age and piping experience of *Bagpipe Hero* listening test participants.

Result	**Tune 1**				**Tune 2**				**Tune 3**		
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3
Bagpipe Hero system score	75	58	92	71	61	90	83	94	57	70	77
All listener ratings (S_A)	49	24	70	32	27	55	45	82	34	28	47
Complete ratings only (S_C)	46	23	69	34	26	56	37	80	27	29	51

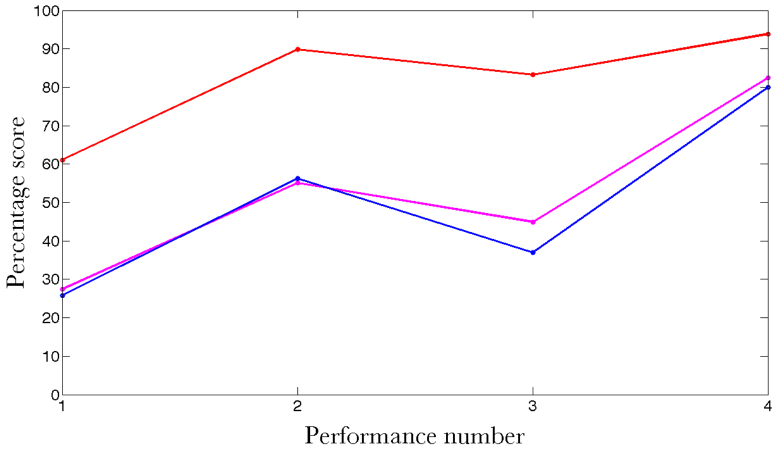
Table 6.20: Mean percentage scores allocated for each tune in *Bagpipe Hero* evaluation.

Result	**Tune 1**				**Tune 2**				**Tune 3**		
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3
Bagpipe Hero system score	2	4	1	3	4	2	3	1	3	2	1
All listener ratings (S_A)	2	4	1	3	4	2	3	1	2	3	1
Complete ratings only (S_C)	2	4	1	3	4	2	3	1	3	2	1

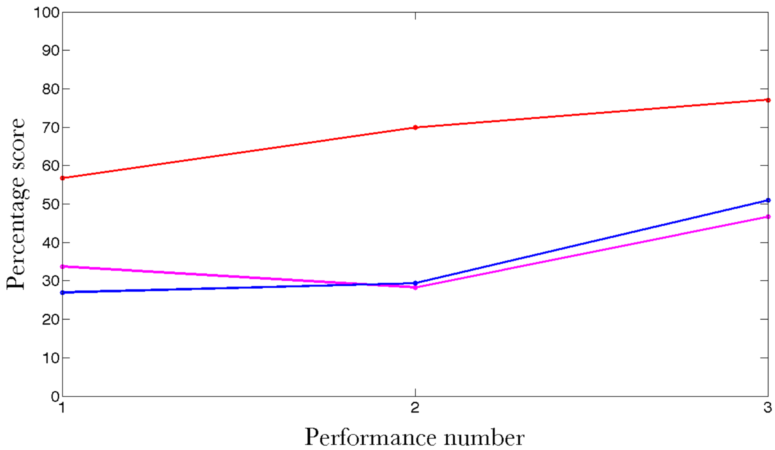
Table 6.21: Ranked order of mean scores for each tune in *Bagpipe Hero* evaluation.



(a) Scores for Tune 1 (“When the Battle’s O’er”).



(b) Scores for Tune 2 (“Scotland the Brave”).



(c) Scores for Tune 3 (“I See Mull”).

Figure 6.12: Plots of percentage scores allocated for each tune in *Bagpipe Hero* evaluation. Red line = scores allocated by *Bagpipe Hero* system; blue line = mean of all listener responses (S_A); purple line = mean of responses from listeners who completed the entire test (S_C).

Comment/technique	**Tune 1**	**Tune 2**	**Tune 3**
Timing	15	11	6
Melody	4	5	4
Ornamentation	13	25	13
Crossing Noises	2	0	0
General Error	13	6	10
General Positive	6	6	6

Table 6.22: Number of references to common techniques and errors in listener responses to *Bagpipe Hero* listening test.

is entirely appropriate for the algorithm to provide high scores for performances that were well executed relative to the player's level of experience.

More importantly, it can be observed that the overall patterns (i.e. the relative differences between performances) exhibit a noticeable alignment between *Bagpipe Hero* scores and listener responses. In terms of ranking the recordings from best to worst, the system output matched with human perception in every instance with the exception of the S_C category for Tune 3, in which the 2nd and 3rd places were reversed (Table 6.21).

In addition to assigning percentage scores, listeners were also asked to provide a brief description of the reasoning behind their evaluation of each recording. Table 6.22 illustrates the number of times various aspects of piping technique (such as timing and ornamentation) were mentioned in these comments, either to describe errors or (to a lesser extent) to highlight positive features of the performance. As in the case of the lesson study (Section 6.3.1), ornament errors were the most common cause for criticism. Mistakes in timing and phrasing were also identified frequently.

One particularly interesting point of comparison between system and listening test scores is the fourth recording (R_4) of Tune 1. In this performance, the player accidentally began with the wrong tune for approximately two bars before recovering to perform the remainder of the piece quite confidently. The plot in Figure 6.12(a) shows that the human listeners judged this serious melody error with a similar degree of severity to the *Bagpipe Hero* system, ranking it slightly behind R_1 and ahead of R_3 (both of which were largely correct in terms of melody, but contained more ornamentation and timing mistakes than R_4). This suggests that the weighting of the various error penalties in the scoring algorithm (Section 5.6.2) provides a reasonable model of how critically a human listener would judge these mistakes, at least in cases where they have been asked to evaluate “the performance as a whole”.

6.7.3 Summary

The scale of this study is not sufficient to claim conclusive proof that the algorithmically generated scores would be aligned with human perception of performance quality in every case. However, these results provide encouraging evidence to suggest that the system can indeed be capable of determining how accurately a performance recreates a given template recording, in a manner that corresponds to subjective judgment of good piping technique.

Similarly, any meaningful analysis of long-term user engagement with the *Bagpipe Hero* system would require a detailed study over an extended period of time. On an informal level, the responses from all players who participated in this single session were extremely positive. In particular, the instructor commented afterwards: *“Well you saw there just the buzz that created [...] and as soon as somebody made a mistake it was like ‘wahaay!’ [referring to the other students’ heckling].”* This enthusiasm from a highly experienced piping instructor, coupled with the numerical results from the listening test, suggests that the current *Bagpipe Hero* application shows promising developments towards a comprehensive game interface to provide motivation and support for Highland piping practice.

6.8 Summary of User Study Outcomes

In this section, the outcomes of the user studies presented in this chapter are collated and summarised. The results are discussed in terms of the three main components of the system. Observations pertaining to the digital chanter itself (both the physical interface and the sound produced) are described in Section 6.8.1. Section 6.8.2 concerns the basic recording, playback and visualisation functions of the GUI program. The effectiveness of the “intelligent” software facilities (i.e. ornament and error recognition/evaluation, and the *Bagpipe Hero* scoring algorithm) is considered in Section 6.8.3.

6.8.1 Digital Chanter Hardware and Sound

The physical feel of the chanter interface was generally well received by participants in both user studies. The students in the lesson study provided a mean response of 4.36/5 ($\sigma = 0.50$) in answer to the survey statement *"I found the physical feel of the digital chanter was realistic to play"*, while P1 in the solo practice study stated *"Very nice feel of material [. . .] the indented holes make it feel like a real chanter which is great"*. However, P4 did express some dissatisfaction with the diameter of some holes, in particular the High A (thumb) hole which he felt was too large, such that it made certain ornaments (e.g. the *strike on High A*) difficult to execute. A new iteration of the digital chanter PCB is currently under development which aims to alleviate this issue by mounting the sensors inside a traditional acoustic chanter; this is discussed further in Section 7.3.

The pressure sensor function was not used extensively in the lesson study, perhaps due to the additional set-up time associated with the full GHB, or the small size of the instructor's room at the school. That said, several lessons were conducted using the chanter in this way. In these instances, the tutor used the pressure gauge on the GUI to illustrate discussions about the technique required to maintain a steady pressure on the bag. Similarly, while the pressure sensor was rarely used in the solo practice study, participants generally agreed that it would be a useful feature for pipers who are unable to practice on a traditional GHB regularly.

Comments regarding the audio output produced when playing the chanter were also largely positive. P1 described it as having a *"lovely crisp sound"* and noted that *"the drones sound great"*, while P2 felt *"it really sounds quite effective"*. P4 (and two of the participants in the *Bagpipe Hero* listening test) took issue with the tuning of certain notes; the preferred intonation of the GHB scale is a matter of some debate (McKerrell, 2011). While this concern is not critical to the system's effectiveness as a practice tool, it would nonetheless be beneficial to provide an interface with which users could adjust individual pitches to prevent the player abandoning the system due to a dislike of the intonation.

In the context of assisting tuition and practice, perhaps a more important characteristic of the sound is the extent to which it allows instances of poor technique to be identified. Standard practice chanters are generally quite poor in this regard compared to the full GHB; as the instructor in the lesson study stated, *"you get away with murder on your practice chanter"*. On this point, the system was described very favourably. The instructor frequently commented that the digital chanter produces a sound that is less *"forgiving"* than its acoustic counterpart (*"This doesn't let you away with anything"*) and is hence a useful tool for identifying technical errors, even in the absence of any GUI feedback. The nature of the comments provided by participants during the *Bagpipe Hero* listening test regarding poorly executed embellishments (e.g. *"doublings too open"*) and other more general complaints (*"sloppy finger work, especially on cross over notes"*) provides further evidence to this effect.

6.8.2 Recording, Playback and Display Functions

The benefits of recording performances during instrumental practice for the purposes of critical listening and self-evaluation are often advocated by teachers and music pedagogy researchers (Klickstein, 2009; Percival et al., 2007). This was alluded to by P4 in the solo practice study (himself an experienced piping instructor), who mentioned owning an audio recorder specifically for this purpose. However, P4 stated that he rarely uses the device (or records performances then never listens to them), the implication being that either the operation of the recorder, or perhaps more likely the process of rewinding and searching for a particular point in the recording is too time-consuming and inconvenient for it to become a regular part of his practice routine.

Therefore, while recording symbolic data from a digital instrument is by no means a new concept, the fact that the system provides a simple means of capturing a performance on the digital chanter and a visual interface with which to navigate the resulting recording is in itself a potentially useful contribution to the Highland piping community. Participants in both user studies were observed to become adept in operating the recording, playback and navigation facilities in a short space of time, and exhibited a range of behaviours in terms of how these features were employed.

The instructor in the lesson studies regularly used the playback function to listen to full pieces recorded by the student. In many cases, these recordings were made with both the tutor and the pupil playing together. Synchronous performance is an essential aspect of Highland piping, however in the control group lessons where the playback function was not available, the majority of playing instances were found to be solo. This may be due to the difficulty of identifying important yet comparatively subtle errors (e.g. poorly executed ornamentation) when playing simultaneously. By performing together then listening to the student's recording individually (which would of course be impossible with a simple audio recorder), the instructor was able to focus on both timing synchrony and detailed fingering technique in turn.

The playback facility was also employed extensively by the participants in the solo practice study. P1 reported listening to recorded performances in full prior to using the ornament and error detection functions. P2 instead used the display to navigate to specific problem phrases, then used the playback to examine them in conjunction with the system's error feedback. Both P3 and P4 used the playback rate control to listen to recordings at slower speeds than the original recording. P3 also discovered an unintentional affordance of the system, using it to practice recording harmony parts to a piece then listening to the two together.

In addition to providing a visual means by which to navigate through recordings, the performance display facility allowed users to examine certain temporal and rhythmic aspects of their playing. During the lesson study, the instructor referred to the visualisation to point out timing discrepancies between his performance and that of the student. Moreover, while the tutor did not employ the ornament detection function, he was observed to use the performance display to illustrate his feedback on ornamentation errors by comparing the shape of good and bad examples of specific embellishments (as shown in the case study described in Section 6.4.3).

In the solo practice study, both P3 and P4 used the visualisation to examine the synchrony between multiple recordings of the same tune. P4 also reported having been surprised to discover that some melody notes in his recordings were of comparable length to (or even shorter than) the gracenotes. The fact that the system can provide a highly proficient and experienced player with a new insight into a fundamental aspect of piping technique suggests that the performance display can indeed be a useful tool for the purpose of self-analysis.

6.8.3 "Intelligent" Software Functions

Of the system tools which incorporate some level of intelligent detection or analysis, the feature which exhibits the most evidence for having been found useful is the false fingering recognition function. During the lesson study, this facility was used frequently to examine the students' recordings, and on several occasions was observed to highlight false fingerings which had apparently gone unnoticed by the instructor (e.g. the case study described in Section 6.4.2). In the solo practice study, P1 also employed this feature regularly. Analysis of the recordings made by P1 before and after the study show that several prominent false fingering errors were eliminated after having been identified and examined using the system over the course of the sessions.

The effectiveness of the crossing noise detection is less clear. During the first week of the lesson study, the instructor pointed out a large number of crossing noises on the display. However, as the study progressed he began to mention them less often. This could be seen to suggest that the algorithm is too sensitive; multiple errors are highlighted in almost every performance, many of which do not in fact correspond to a clearly audible crossing noise.

A similar conclusion could be drawn from the fact that P3 (who did not consult the error detection function frequently but rather used the playback facility to analyse his playing) was found to have a greater number of crossing noise annotations in the recordings made after the study. This interpretation can be countered by the observation that the other participants did achieve fewer crossing noises in almost all instances. Nonetheless, it may be beneficial to provide the user with some control over the sensitivity of the crossing noise detection in order to prevent them being discouraged or irritated by an abundance of red circles on every recording. Players could then gradually increase the sensitivity as their technique improves (or as P2 put it, *"when I'm ready to do the Northern Meeting [highly prestigious piping competition] I can get right down to the milliseconds and have another go"*).

As mentioned above, the ornament detection facility was almost never used during the lesson study. This is perhaps unsurprising, as the instructor quickly became adept at identifying embellishments directly from the performance display without the need for them to be highlighted by the system, and his expert feedback on their execution is naturally far more nuanced than that of the automatic evaluation function. The ornament analysis feature was used more often in the solo practice sessions, particularly by P2, who rated its usefulness at 5/5 and whose performance was shown to improve with regard to ornamentation errors over the course of the study.

The ornament recognition algorithm also plays a critical role in the operation of the *Bagpipe Hero* application. From the comments provided by participants in the listening test (Section 6.7.2) it can be observed that ornamentation errors were the most common criticism of the performances. It is therefore essential that the ornament detection algorithm performs effectively in order to model expert perception of traditional GHB performance quality. The results of the listening test, while by no means conclusive, indicate an encouraging level of alignment between the scores generated by the *Bagpipe Hero* system and those assigned by the human listeners.

Chapter 7

Conclusions

This thesis has presented a complete hardware and software system designed to support the GHB learning process, and investigated its effectiveness in a series of user studies with both novice and expert pipers. The contributions of this work are summarised in Section 7.1. Section 7.2 reflects on the processes and outcomes of the project, both in terms of the specific field of Highland piping and how they might relate to other musical traditions. Avenues for further research are identified in Section 7.3, and the thesis concludes with some closing remarks concerning the design of technologies for specific cultural contexts in Section 7.4.

7.1 Thesis Contributions

Digital Chanter Hardware Interface

A digital bagpipe chanter interface is presented, which uses continuous infrared reflectance sensors mounted inside the holes of a 3D printed chanter exterior to measure the player's finger movements. This avoids the moisture-sensitivity issues associated with the capacitive touch sensors used in existing electronic bagpipes, and provides a physical playing experience which is closer to that of an acoustic chanter than the contact-dependent capacitive sensing approach.

The chanter also incorporates an air pressure sensor which allows it to be connected to a standard acoustic GHB and controlled in the traditional manner by exerting pressure on the bag with the arm. This allows the user to practice the blowing and bag pressure aspects of piping technique in situations where playing an acoustic bagpipe would be impractical (e.g. due to volume constraints).

The continuous sensors allow a rich symbolic representation of the player's performance to be captured by the accompanying software system. Moreover, while this thesis has focussed exclusively on traditional Highland piping, the capabilities of the interface to allow novel techniques to extend the behaviour of the GHB could be readily explored in future work.

Ornament Detection and Evaluation Algorithm

Engaging with the highly formalised nature of GHB ornamentation, a DTW-based pattern matching algorithm was developed to detect and evaluate a wide range of Highland piping embellishments in performances recorded using the digital chanter. The method was evaluated using a dataset of 30 recordings by expert and student pipers (containing a total of 3629 hand-annotated ornaments) and shown to provide an overall recognition accuracy result of 93%. In cases where a detected embellishment contains errors, these can be identified by the system and relayed to the user. Lastly, the potential of the ornament recognition algorithm for automatic transcription of bagpipe music is demonstrated. This is a hitherto unexplored endeavour, and one which could be of considerable benefit to the piping community.

GUI Application for Lessons and Solo Practice

A custom GUI application was developed to assist in Highland piping tuition and solo practice. The program uses sensor input from the digital chanter, and provides controls for recording, playback and visualisation of performances. The software also incorporates the ornament recognition and evaluation algorithm, and additional facilities for the identification and description of GHB-specific fingering errors (false fingerings and crossing noises). A series of user studies was conducted to investigate the effectiveness of the complete hardware and software system in lesson and solo practice situations. The system was well received by both expert and novice pipers, and a range of usage patterns was observed in terms of how it contributed to the different learning environments.

Bagpipe Hero **Game Interface**

The ornament and error detection functions were also incorporated into a game interface, *Bagpipe Hero*, with the aim of increasing motivation to practice among piping students. Users can play along to an exemplar recording of a particular piece, attempting to match the embellishments and phrasing as closely as possible. Scores are assigned based on the accuracy of the melody (in terms of both pitch and timing) and ornamentation, and the top 5 scores for each tune are displayed on a leader board. A preliminary evaluation of the scoring system, in the form of a listening test with 12 pipers, indicates an encouraging degree of alignment between the algorithmically generated scores and those assigned by the human listeners with regard to performance quality.

7.2 Reflections

This section presents some personal reflections on the processes and outcomes of this work, both in terms of the specific field of traditional Highland piping and how they relate to the wider domain of instrumental learning in general. Firstly, the experience of developing and testing the various iterations of the digital chanter has illuminated the extent to which an electronic instrument must replicate the physical feel and playing characteristics of its acoustic counterpart to be effective as a practice tool.

This may seem an obvious point. That said, both user feedback and first-hand testing have illustrated how seemingly minor inaccuracies in sensor calibration can render the response of the chanter wholly unrealistic with regard to the extremely small and fast finger movements involved in GHB ornamentation. Since the aim of technological support for instrumental practice is explicitly to allow techniques learned on the digital interface to be transferred back to the acoustic instrument, the importance of recreating the traditional playing experience cannot be overstated.

On a related topic, it can be observed that the features of a system which relate most closely to *what users already do* are likely to be among the most warmly received. For example, the “unforgiving” sound produced by the digital chanter was one of the most frequently complemented aspects of the system, and there is evidence from the user studies to suggest that this may in fact be more useful for the identification of certain errors (particularly crossing noises) than the "intelligent" method of highlighting them on screen. This is not to say that automatic error detection and feedback cannot be beneficial; false fingerings are often almost impossible to hear on an acoustic chanter, and ornamentation errors can be difficult to diagnose beyond simply "that sounded wrong", especially for inexperienced players. However, this idea does illustrate the general importance of connecting with users' existing technique and expertise when designing tools to support a particular musical tradition.

Moreover, it can be noted that to develop a clear and complete understanding of the requirements of a system demands regular user testing in different environments, as the designer's conception of what is needed will very often be somewhat biased. As an example, perhaps the most pressing issue regarding bagpipe practice for the author (being resident in a flat in London) is the inability to play the full GHB at home, and thus maintain the necessary levels of physical endurance required for lengthy public performances. For this reason, the pressure sensor facility was deemed so important that an early version of the system overlooked the possibility that users might wish to play the chanter without blowing; the only way to deactivate the pressure sensor was to set the "reed strength" threshold to 0. The first user test participants who attempted to use the chanter in this way quickly became understandably frustrated by having to click and drag a GUI slider to turn the sound on or off.

Lastly, the field of technology to support instrumental practice can be seen as a continuum between simple recording/playback devices on one hand and fully automated intelligent tutoring systems on the other, and it is important to consider where a new system (and its constituent components) should be positioned on this spectrum. Certain aspects of some musical traditions are highly formalised (in the case of Highland piping, ornamentation and the correct fingering for each note), and can readily be evaluated by an appropriate algorithm with a high level of accuracy. However, as noted in (Holland, 2000) music education is generally an open-ended domain, and hence a more exploratory approach to teaching and learning is often preferable to an overly-prescriptive intelligent system.

This relates to the observation discussed in Section 6.5.4 concerning the fourth case study (Section 6.4.4), which demonstrates that the system can be "wrong" and still be useful in terms of offering meaningful insight into the performance. This highlights the importance of presenting information in manner that encourages the user to explore and interpret the data for themselves, such that the addition of intelligent detection features can augment, rather than inhibit, the crucial process of critical self-reflection in musical instrument learning.

7.3 Future Work

The work described in this thesis provides several avenues for future research and development. Firstly, the physical feel of the digital chanter could be further refined by mounting the sensors inside a real acoustic GHB chanter. An early prototype for this new PCB design has already been developed, and this work is ongoing. The improved PCB will also incorporate audio circuitry to allow the chanter to generate sound directly, without the need to be connected to a computer. Furthermore, the response of the interface could be enhanced by making full use of the continuous output of the sensors to implement sliding between notes (e.g. using a physical modelling approach).

Given the highly formalised nature of GHB ornamentation, it is possible that the performance of the ornament detection algorithm could be improved by the addition of a more sophisticated rule-based layer (compared to the current rules which simply outline permitted previous and subsequent notes) to complement of the DTW process. However, a more useful development might be to enrich the feedback provided by the system with regard to ornamentation errors. The instructor in the lesson studies used visual comparison between good and bad embellishments to illustrate his feedback (Section 6.4.3), so an interface to display the player's ornament alongside an archetypal example could be a useful starting point. The potential of the ornament recognition algorithm to allow automatic transcription of GHB music is also an exciting prospect, and one which would benefit from further research.

A possible improvement for the GUI application itself would be the introduction of different feature levels, which could be activated or removed according to the player's level of experience. For example, a novice player may be well served by a display which simply illustrates the current note being played, and identifies whether or not the fingering is correct. The design of intuitive and appropriate graphical interfaces for a particular user group is a subtle yet crucial issue, and continued research into how best to develop such a system to support Highland piping would almost certainly yield useful results.

Lastly, it would be interesting to examine the motivating effect of the *Bagpipe Hero* system in a longitudinal study, and to investigate the extent to which the player's technique develops over time, perhaps compared to a more traditional learning methodology. Given the interest in whether musical computer games can increase instrumental skill (Richardson & Kim, 2011), such a study could be of interest not only to bagpipe players and instructors, but also to the wider academic community associated with musical instrument pedagogy.

7.4 Closing Remarks

The work presented in this thesis is an example of a digital interface designed to connect to a long established and highly formalised musical tradition. The success of such systems is dependent not only on practical considerations such as appropriate sensing and mapping strategies, but also, critically, on ensuring that the particular constraints and implications of the cultural context are inherent in the design. By integrating support for the ornamentation and fingering techniques that are a central aspect of traditional Highland piping practice, and through careful consideration of the specific challenges faced in teaching and learning the bagpipes, this work demonstrates how digital technologies can provide a meaningful contribution to even the most conservative musical genres.

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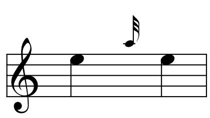
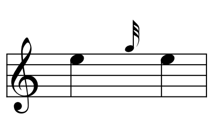
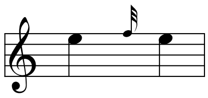
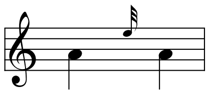
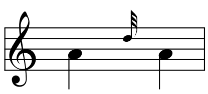
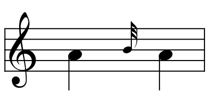
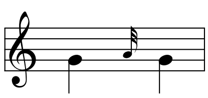
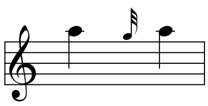
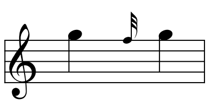
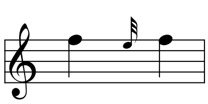
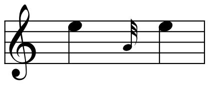
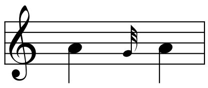
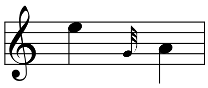
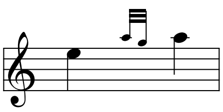
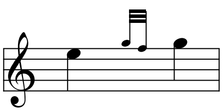
Appendix A

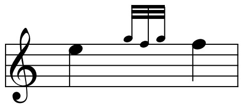
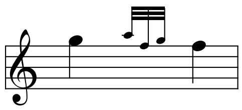
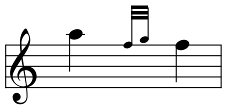
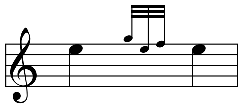
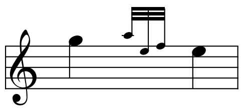
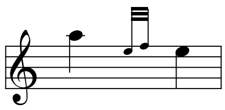
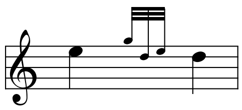
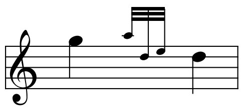
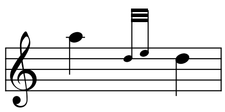
Table of Highland Piping Ornamentation

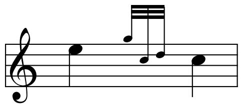
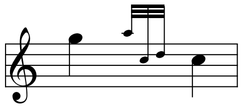
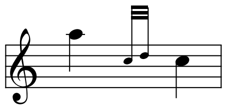
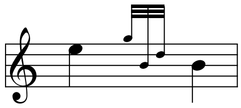
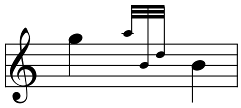
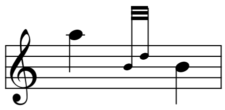
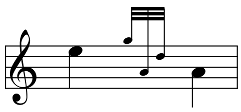
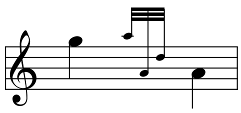
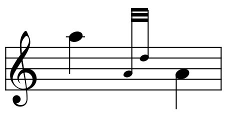
This appendix provides a table of all embellishments that are detectable using the ornament recognition algorithm described in Chapter 4. The traditional Highland bagpipe scale is comprised of nine notes from G (sounding pitch G♯) above middle C (“Low G”) to the A of the next octave (“High A”). For succinctness, columns 3 to 5 in the table use the terms G and A to refer to Low G and Low A, with High G and High A being denoted by G’ and A’ respectively. By convention, the C♯ and F♯ in the piping scale are called simply C and F. However, since C♮ and F♮ can also be reproduced through non-standard cross fingerings, these notes are included in the table where appropriate.

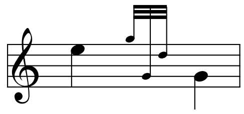
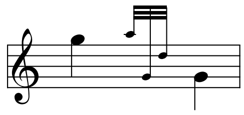
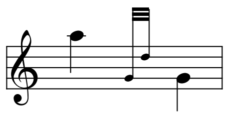
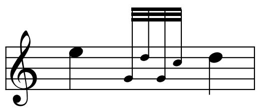
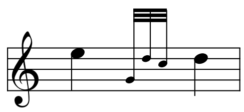
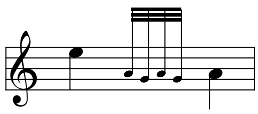
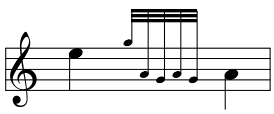
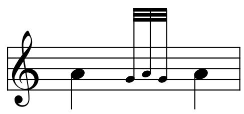
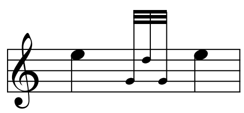
Name	**Notation**	**Constituent Gracenotes**	**Possible Previous Notes**	**Possible Subsequent Notes**
High A Gracenote		A’	G, A, B, C♮, C, D, E, F♮, F, G’	G, A, B, C♮, C, D, E, F♮, F, G’
High G Gracenote		G’	G, A, B, C♮, C, D, E, F♮, F	G, A, B, C♮, C, D, E, F♮, F

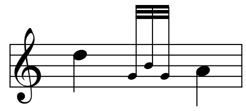
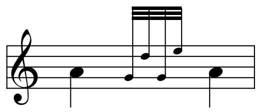
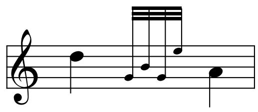
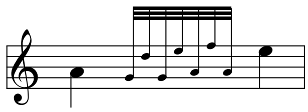
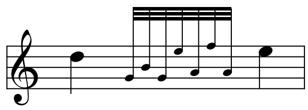
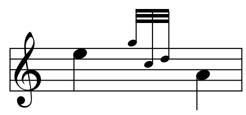
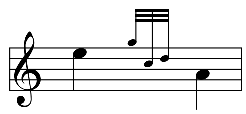
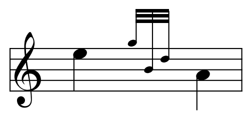
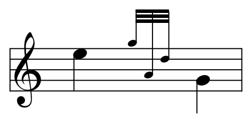
F Gracenote		F	G, A, B, C♮, C, D, E	G, A, B, C♮, C, D, E
E Gracenote		E	G, A, B, C♮, C, D	G, A, B, C♮, C, D
D Gracenote		D	G, A, B, C♮, C	G, A, B, C♮, C
C Gracenote		C	G, A, B	G, A, B
B Gracenote		B	G, A	G, A
Low A Gracenote		A	G	G
Strike on High A		G'	A'	A'
Strike on High G		F	G'	G'
Strike on F		E	F	F

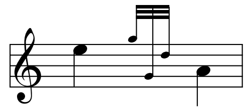
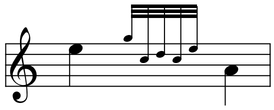
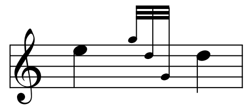
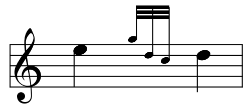
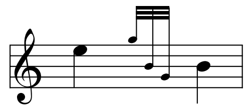
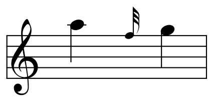
Strike on E		A	E	E
Strike on D (heavy)		G	D	D
Strike on D (light)		C	D	D
Strike on C		G	C	C
Strike on B		G	B	B
Strike on Low A		G	A	A
Strike to Low A (“bow”)		G	B, C♮, C, D, E, F♮, F, G’, A’	A
High A doubling		A’, G’	G, A, B, C♮, C, D, E, F♮, F, G’	A’
High G doubling		G’, F	G, A, B, C♮, C, D, E, F♮, F, A’	G’

F doubling		G’, F, G’	G, A, B, C♮, C, D, E, F♮, F	F
F doubling from High G		A’, F, G’	G’	F
F half doubling		F, G’	G’, A’	F
E doubling		G’, E, F	G, A, B, C♮, C, D, E, F♮, F	E
E doubling from High G		A’, E, F	G’	E
E half doubling		E, F	G’, A’	E
D doubling		G’, D, E	G, A, B, C♮, C, D, E, F♮, F	D
D doubling from High G		A’, D, E	G’	D
D half doubling		D, E	G’, A’	D

C doubling		G’, C, D	G, A, B, C♮, C, D, E, F♮, F	C
C doubling from High G		A’, C, D	G’	C
C half doubling		C, D	G’, A’	C
B doubling		G’, B, D	G, A, B, C♮, C, D, E, F♮, F	B
B doubling from High G		A’, B, D	G’	B
B half doubling		B, D	G’, A’	B
Low A doubling		G’, A, D	G, A, B, C♮, C, D, E, F♮, F	A
Low A doubling from High G		A’, A, D	G’	A
Low A half doubling		A, D	G’, A’	A

Low G doubling		G’, G, D	G, A, B, C♮, C, D, E, F♮, F	G
Low G doubling from High G		A’, G, D	G’	G
Low G half doubling		G, D	G’, A’	G
Throw on D (heavy)		G, D, G, C	A, B, C♮, C, D, E, F♮, F, G’, A’	D
Throw on D (light)		G, D, C	A, B, C♮, C, D, E, F♮, F, G’, A’	D
Birl		A, G, A, G	G, B, C♮, C, D, E, F♮, F, G’, A’	A
Birl with High G Gracenote		G’, A, G, A, G	G, A, B, C♮, C, D, E, F♮, F	A
Birl from Low A		G, A, G	A	A
Grip		G, D, G	A, B, C♮, C, E, F♮, F, G’, A’	A, B, C♮, C, D, E, F♮, F, G’, A’

Grip from D		G, B, G	D	A, B, C♮, C, D, E, F♮, F, G’, A’
Taorluath		G, D, G, E	A, B, C♮, C, E, F♮, F, G’, A’	G, A, B, C♮, C, D
Taorluath from D		G, B, G, E	D	G, A, B, C♮, C, D
Crunluath		G, D, G, E, A, F♮, A	A, B, C♮, C, E, F♮, F, G’, A’	E
Crunluath from D		G, B, G, E, A, F♮, A	D	E
Tachum on C*		G’, C, D	G, A, B, C♮, C, D, E, F♮, F	G, A, B, C♮
Tachum on C♮*		G’, C♮, D	G, A, B, C♮, C, D, E, F♮, F	G, A, B, C
Tachum on B*		G’, B, D	G, A, B, C♮, C, D, E, F♮, F	G, A, C♮, C
Tachum on A*		G’, A, D	G, A, B, C♮, C, D, E, F♮, F	G, B, C♮, C

Tachum on G*		G’, G, D	G, A, B, C♮, C, D, E, F♮, F	A, B, C♮, C
GDE cutting*		G’, C, D, C, E	G, A, B, C♮, C, D, E, F♮, F	G, A, B, C♮, C
Gracenote-strike on D (heavy)*		G’, D, G	G, A, B, C♮, C, D, E, F♮, F	D
Gracenote-strike on D (light)*		G’, D, C	G, A, B, C♮, C, D, E, F♮, F	D
Gracenote-strike on B (heavy)*		G’, B, G	G, A, B, C♮, C, D, E, F♮, F	B
F push to High G*		F	A’	G’

*not included in original implementation of OR$_{2012}$ algorithm.

Appendix B

Participant Survey for Pilot Study (March 2013)

During the pilot study of the prototype GUI system described in Section 5.3, participants were asked to complete a Likert-style survey describing their experience with the system. The complete survey is provided on the following page.

Digital Bagpipe Chanter Study - Gordonstoun School
Participant Survey

Age: **Gender:** **Number of years playing bagpipes:**

1. **I found the physical feel of the digital chanter was realistic to play.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

2. **I found the sound quality of the digital chanter to be realistic.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

3. **I found the digital chanter system easy to use.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

4. **I found the display easy to understand.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

5. **I found the system fun to use.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

6. **I think the system would be useful as a practice tool.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

7. **I would use the digital chanter system in my lessons and practice.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

8. **If you have any other comments about using the digital chanter system, or suggestions for future developments/improvements, please write them below (if additional space is required, please continue on reverse of page):**

THANK YOU FOR YOUR PARTICIPATION

Appendix C

Participant Surveys for Main Lesson Study (May-June 2014)

As part of the lesson study with the complete digital bagpipe system described in Chapter 6, the students were asked to complete Likert-style surveys before and after participation. These introductory and concluding surveys are provided on the following pages.

Participant ID:

Digital Bagpipe Chanter Study - Gordonstoun School – May/June 2014
Introductory Survey

Age: **Number of years playing bagpipes:** **Number of tunes learned:**

1. In general, I find it easy to play in time with a beat and/or with other musicians.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

2. I believe that if I ever do make timing errors, I am always aware of it.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

3. In general, I find it easy to execute all piping ornaments correctly.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

4. I believe that if I ever do make ornamentation errors, I am always aware of it.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

5. In general, I find it easy to change between notes without making crossing noises.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

6. I believe that if I ever do make crossing noises, I am always aware of it.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

7. In general, I feel that I play all of the tunes I know without using false fingerings.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

8. I believe that if I ever do make false fingering errors, I am always aware of it.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

Participant ID:

9. I enjoy practicing the bagpipes.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

10. I enjoy weekly bagpipe lessons.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

11. I enjoy playing in a pipe band.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

12. I enjoy playing the bagpipes as a soloist.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

13. I feel motivated to improve as a piper.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

THANK YOU FOR YOUR PARTICIPATION

Participant ID:

Digital Bagpipe Chanter Study - Gordonstoun School – May/June 2014
Concluding Survey

Age: **Number of years playing bagpipes:** **Number of tunes learned:**

1. **In general, I find it easy to play in time with a beat and/or with other musicians.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

2. **I believe that if I ever do make timing errors, I am always aware of it.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

3. **In general, I find it easy to execute all piping ornaments correctly.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

4. **I believe that if I ever do make ornamentation errors, I am always aware of it.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

5. **In general, I find it easy to change between notes without making crossing noises.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

6. **I believe that if I ever do make crossing noises, I am always aware of it.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

7. **In general, I feel that I play all of the tunes I know without using false fingerings.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

8. **I believe that if I ever do make false fingering errors, I am always aware of it.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

9. I enjoy practicing the bagpipes.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

10. I enjoy weekly bagpipe lessons.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

11. I enjoy playing in a pipe band.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

12. I enjoy playing the bagpipes as a soloist.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

13. I feel motivated to improve as a piper.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

14. I found the physical feel of the digital chanter was realistic to play.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

15. I found the digital chanter was fun to use.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

16. I think the system would be useful as a practice tool.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

17. If you have any other comments about using the digital chanter system, or suggestions for future developments/improvements, please write them below:

THANK YOU FOR YOUR PARTICIPATION

Appendix D

Participant Survey for Solo Practice Study

Following the solo practice study with the full digital chanter system described in Section 6.6, participants were asked to complete a Likert-style survey describing their experience with the system. The complete survey is provided on the following page.

Participant name: **Number of years playing bagpipes:**

Solo Practice Study with Digital Bagpipe Chanter System – Concluding Survey

1. **I used the performance visualisation/display facility:**

Never	Rarely	Sometimes	Frequently	Very Frequently

2. **I found the performance visualisation/display facility useful.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

3. **I used the performance playback facility:**

Never	Rarely	Sometimes	Frequently	Very Frequently

4. **I found the performance playback facility useful.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

5. **I used the ornament detection/feedback facility:**

Never	Rarely	Sometimes	Frequently	Very Frequently

6. **I found the ornament detection/feedback facility useful.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

7. **I used the ``Display Errors" facility:**

Never	Rarely	Sometimes	Frequently	Very Frequently

8. **I found the false fingering detection useful.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

9. **I found the crossing noise detection useful.**

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

10. I used the air pressure sensor facility:

Never	Rarely	Sometimes	Frequently	Very Frequently
☐	☐	☐	☐	☐

11. I found the air pressure sensor facility useful.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
☐	☐	☐	☐	☐

THANK YOU FOR YOUR PARTICIPATION