EpipE: Exploration of the Uilleann Pipes as a potential controller for computer-based music

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ABSTRACT
In this paper we present a design for the EpipE, a new expressive electronic music controller based on the Irish Uilleann Pipes, a 7-note polyphonic reeded woodwind. The core of this proposed controller design is a continuous electronic tonehole-sensing arrangement, equally applicable to other woodwind interfaces like those of the flute, recorder or Japanese shakuhachi. The controller will initially be used to drive a physically-based synthesis model, with the eventual goal being the development of a mapping layer allowing the EpipE interface to operate as a MIDI-like controller of arbitrary synthesis models.

Keywords
Controllers, continuous woodwind tonehole sensor, uilleann pipes, Irish bagpipe, physical modelling, double reed, conical bore, tonehole.

1. INTRODUCTION
A musician's performance is intimately bound up with their physical means of expression. This relationship is equal parts struggle and dialogue – the instrument constrains, but its unique character colours and informs the performance. Until now, much of the focus in electronic musical interface design has concentrated on the keyboard, leaving many instrumental musicians at a loss when faced with a computer. The wind and string communities have been particularly poorly served – the more 'organic' nature of their interaction with their instrument making it much harder to measure meaningfully.

A number of flute and clarinet-style interfaces have been developed in the past, Akai's EWI and Yamaha's WX series of controllers being notable examples, but these fail to provide continuous tonehole control, a feature particularly important for players of open-holed folk woodwinds like the pipes, tin-whistle or traditional flute. Performers of Irish, Scottish, Breton and other folk musics make heavy use of sliding and half-holing techniques, and a controller that doesn't allow for this drastically restricts their range of expressive possibilities. The tonehole problem has been considered by some investigators, in the context of keyed woodwinds at least. Gary Scavone of CCRMA built the *Holey Controller[1]*, modifying a Yamaha WX11 to give a degree of continuous control by adding force sensing resistors under the keys, but this was primarily to provide him with a means of controlling his multiple-tonehole physical model of a clarinet. For a real instrument, the parameter of interest is the degree to which the player's finger is covering the tonehole rather than the force with which it is applied.

The Irish Uilleann Pipes, a polyphonic reeded woodwind (described more fully in the next section of this paper), provides an interesting basis for a new electronic interface. Like the Scottish Pipes, air is continually provided to the instrument and it is therefore completely finger-articulated. Unlike the Scottish pipes, the sound of the instrument may be stopped during play, allowing for staccato as well as legato playing and a wide range of tone colours and dynamic variation, greatly increasing the range and complexity of instrumental gesture. This combination of factors makes it an ideal test-bed for a new tonehole-sensor. Another feature of the instrument unusual in a member of the woodwind family is that it allows the player to provide their own chordal accompaniment using the regulators, a set of keyed pipes played with the wrist.

2. THE UILLEANN PIPES
A brief description of the Uilleann Pipes is provided here to render this document more intelligible to those unfamiliar with the instrument.

2.1 Physical Design
A set of Uilleann Pipes (see Figure 1) generally consists of:

- Bag
- Bellows
- Chanter
- Drones (3)
- Regulators (typically 3, though as many as 5 have been known)

The *bag* or air reservoir on the Uilleann Pipes is inflated by means of a *bellows*. The bellows are attached by a belt to the player's waist and by a length of flexible tubing to the bag.

The *Chanter*, attached to the neck of the bag, is the main melody instrument and has a range of two octaves, very unusual among bagpipes. Its tonehole arrangement is similar to that of the recorder, though the fingering is very different and the bottom of the chanter effectively serves as an extra hole, played by raising and lowering it from the knee.

The *Drones* supply a continuous 'drone' accompaniment to the melody. Each drone is tuned by means of a slide – the tenor to the bottom note of the chanter, the baritone an octave lower and the bass an octave lower again.

The *Regulators* are keyed chanters and are used to provide a chordal accompaniment. The end of each regulator is sealed, so the regulator remains silent until a key is pressed. The three most usual regulators (tenor, baritone and bass) lie side-by-side across the player's knee with the bass on the outside, near the chanter, the tenor on the inside, and the baritone between them. The bass and baritone each have four keys and the tenor five.

Figure 1: Set of D Uilleann Pipes made by the Taylor brothers, Chicago circa 1890

Both Drones and Regulators are mounted on a common stock which is connected to the body of the bag and rests across the player's knee.

2.2 Playing Technique

The pipes are usually played sitting down so as to allow the regulators and chanter to rest on the knee. They are operated by the elbow of one arm while the bag is held under that of the other and used to maintain a steady supply of air to the rest of the instrument. The main factor determining the range of bag pressure to be applied is the chanter reed – those of the drones and regulators are of more straightforward construction and can normally be adjusted to match it. The chanter reed plays in quite a narrow range of bag pressure: too little and the reed will not sound; too much and it will blow closed. The drones, along with the regulators, lie across the player's knee on the bellows-side, and may be activated or deactivated using a wrist-operated toggle switch.

2.2.1 The Chanter

The Uilleann pipe chanter, though tuned differently, has an identical tonehole arrangement to that of the Scottish bagpipe chanter. Of the seven toneholes on the front of the instrument, the top three are covered with the 1st through 3rd fingers of one hand (usually the left) and the remaining 4 with the 1st through 4th fingers of the other. The topmost tonehole is on the back of the chanter and is covered with the thumb of the upper hand.

The Uilleann pipe chanter differs from that of other bagpipes in three major respects:

1. Its reed, like that of the oboe, is a double reed which can be overblown into the second octave, effectively doubling its range.

2. The open end of the chanter serves as an extra hole. The chanter is usually played resting on the knee, allowing the player to stop the sound abruptly between notes by covering all the toneholes. This enables the performer to play "tight" staccato passages as well as the legato stream of notes to which players of other bagpipe instruments are restricted. Notes of the scale are played with just one or two of the toneholes uncovered, facilitating rapid staccato runs and allowing the performer to modulate the tone by uncovering lower toneholes and/or raising the chanter from the knee. Vibrato may be achieved by rapidly uncovering and re-covering the lower toneholes and, optionally, raising the chanter from the knee to produce a more strident tone.

3. The bottom note of the chanter can be played in two different pressure regions, one producing a tone similar to that of the other notes of the lower octave, the other a much stronger tone, known as the "hard" bottom D which can be used to great ornamental effect.

As with other open-holed folk woodwinds, much use is made of the technique of "sliding" from a lower note to the note above and of rapid grace notes.

Figure 2: Principal author playing a set of pipes pitched in D

2.2.2 The Regulators

The Regulators lie across the player's knee on the same side as the player's lower chanter hand and are usually played using the wrist of the this hand, though while playing certain notes the hand may be removed from the chanter to finger more complex chords.

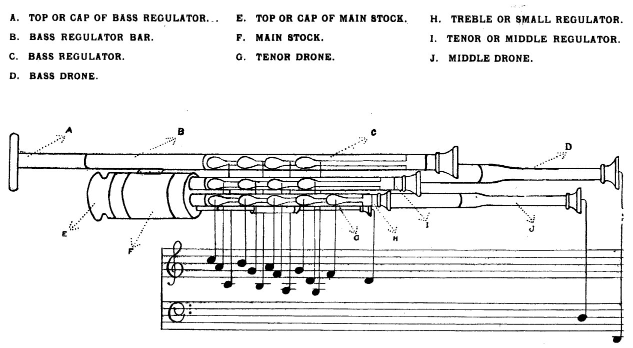


Figure 4: Regulator Tuning Diagram[2]

When played with the wrist, the upper four rows of regulator keys may be struck singly or in chords of two or three notes across a row. The 5th note on the tenor regulator is usually played in combination with the lowest note on the baritone. These notes and chords may be sustained or used for rhythmic effect.

3. DESIGN OF THE EPIPE INTERFACE

There are two parallel strands to the development of the EpipE interface: the physical design of the controller and the construction of an appropriate synthesis model with which to test the design.

3.1 Physical Controller Design

During the initial phase of development, we considered the instrument itself and the way it is played in an effort to identify the parameters to be measured and determine appropriate ranges, resolutions and sampling rates for them. Starting with these observations, we have sketched a design outline for the interface prototype and have made substantial progress in the process of designing and constructing the required electronic circuitry.

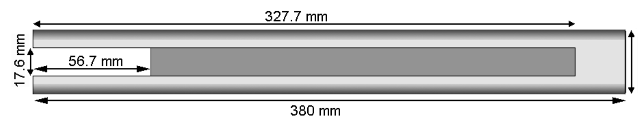
3.1.1 The Bag and Bellows

The air pressure in the bag is a function of the force applied by the player's elbow. One means of quantifying this parameter would be to attach a pressure sensor to a sealed bladder. The other obvious solution is to measure the applied force directly using a force-sensing resistor. We have chosen the second approach for reasons of cost and ease-of-integration.

The Bellows serve the purely mechanical purpose of filling the bag with air to drive the reeds. As no air flow is required through our electronic interface we have opted to discard the bellows, thereby easing the task of playing the regulators.

3.1.2 The Chanter

The EpipE chanter consists of a 3D-printed tube-like frame housing two printed circuit boards and a momentary switch. The frame is a flattened oval in cross-section, approximately 38 cm in length, and has slots front and back for the circuit boards. The front board is a four layer PCB 17.6 mm across and 328 mm in length. It has seven holes along its length, whose spacing and dimensions are based on measurements taken from a number of instruments in the principal author's possession. The back board is of identical cross section, 57 mm in length, and contains the thumb-hole and its supporting circuitry. The perimeters of both PCBs are routed to a depth of 1.2 mm (half the board thickness), allowing them to be mounted securely in their respective slots in such a way as to be flush with the wall of the frame.



Plan View

Cross Section

Figure 3: EpipE Chanter

3.1.2.1 The Tonehole Sensor

The selection of an appropriate technology for the chanter tonehole sensor has proved to be the biggest challenge encountered to date in the development process. The length of the air column, which determines the pitch produced, is predominantly governed by the position of the first opening in the bore of the instrument; therefore the particular parameter we want to measure is degree of tonehole coverage. More specifically, we must measure the degree of tonehole edge coverage, as the player's finger may begin to cover or uncover the hole from a range of different angles. The tactile feedback provided by the feel of the tonehole edges is an important aid to the player of the real instrument, and for this reason a flat plate-style sensor would be unsuitable for our purposes.

Numerous approaches have been considered, most involving optical or capacitive technologies, or a combination of the two. The idea of using capacitive sensing in its analogue range was discarded due to its extreme sensitivity to variations in humidity, skin-conductivity and other environmental variables. Likewise, the optical solutions considered would have been susceptible to variations in ambient light and, in some cases, to variations in the levels of infrared radiation emitted by the performer. An instrument built using any of these approaches would need to be calibrated to each individual user and set of conditions, and would not provide the clean open, closed and partially covered readings required for a robust electronic interface.

We eventually decided to experiment with a number of capacitive touch sensors spaced evenly around the rim of the tonehole. The advantage of this approach is its reliability – each individual switch is either definitely on or definitely off – but the drawback is that a relatively high number of switches is required to approximate an analogue range. The issue is not the frequency resolution required for held notes – over the semitone to full-tone intervals involved, a relatively small number of sensors would suffice – but rather the resolution required while sliding between notes. Some of the technologies used in fingerprint sensors would be ideal for the task, as would those used in some laptop pointing devices. Regrettably, these are usually implemented as custom-designed microelectronic devices and none are available in the unusual form factor we require.

Our first tonehole prototype was built using discrete analogue components and comprised six individual capacitive touch-sensor circuits connected to electrodes mounted around the edge of a hole. The number is of no particular significance, but worked out conveniently in terms of the electronic components involved and was deemed sufficient to test the reliability of our solution. These sensors were connected as inputs to a PIC microcontroller and used to drive a single-hole clarinet model provided with Perry R Cook's Signal Processing Toolkit[3] and some single-hole flute models of our own, with the expected results. Even with the limited resolution of our prototype, it was possible to consistently produce sounds corresponding to fully open and fully closed tonehole states as well as a satisfactory semitone. Attempts to slide, however, produced stepped tones rather than smooth legato, highlighting the need to increase the sensor density to the point where each touch electrode corresponds to a change in frequency of less than the Just Noticeable Difference discernible by the human ear. The JND varies with frequency, but can be taken to be about 1/12th of a semitone in the frequency range of interest in our work [4]. Filtering the composite sensor signal to conceal its stepped characteristic is not appropriate in the context of a performance instrument, as this would introduce an unacceptable delay of somewhere around 30ms (the shortest measured duration for a complete finger gesture in a sample of fast, staccato piping).

For the second prototype we increased the number of electrodes-per-hole to sixteen. In this denser system, dedicating a touch-sensor circuit to each electrode would have entailed a prohibitive component count. Instead, we chose to use a single capacitive touch-switch circuit and to multiplex the tonehole sensor-pads using some new analogue switches with ESD protection manufactured by Maxim. This arrangement, detailed below, provides a satisfactory sliding effect between notes and forms the basis of our multi-tonehole circuit. Multiplexing the tonehole-sensor pads has enabled us to reduce the circuitry considerably and poll all 128 pads at a rate of 100 Hz using just two touch-plate sensor sub-circuits.

Figure 5 is a simplified representation of the sensing circuitry for a single electronic tonehole. A high frequency oscillator feeds the top node of an RC (Resistor-Capacitor) potential divider. A capacitance, the parallel combination of parasitic capacitances to ground and the capacitance of a tone-hole pad to ground, forms the lower half of the divider. When the player's finger is in contact with the pad this capacitance typically increases several fold, thereby causing the voltage at the centre node of the potential divider to fall in magnitude. This drop is detected by comparing its peak value to a reference voltage. By multiplexing all the tone-hole pads to the centre node of the potential divider, one peak-detect / comparator circuit can service a much larger number of tonehole pads. The microcontroller manages the multiplexer addressing and converts the sensor signals to a custom serial protocol for output.

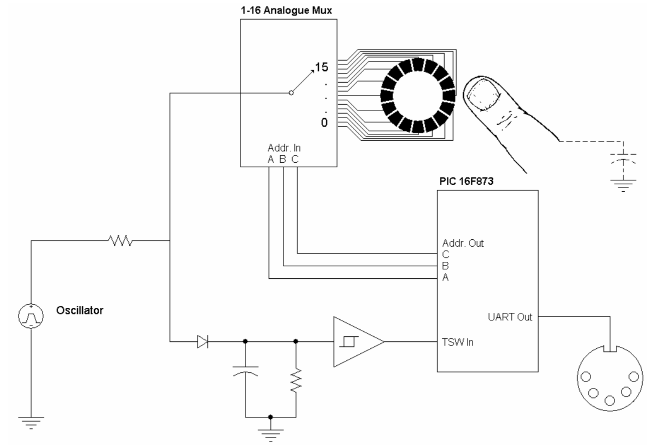


Figure 5: Block Diagram of Single EpipE Tonehole

3.1.3 Drones and Regulators

The drones and regulators of the EpipE will be realised as a set of switches which connect directly to a distribution board mounted in the modified stock of a real set of pipes. The switches' states are multiplexed and monitored by the PIC on the chanter PCB. The distribution PCB also houses various housekeeping sub-systems, including an RS-232 driver, an FSR circuit for bag pressure measurement and power supply circuitry.

The interface to the drones is a simple wrist-operated on-off toggle switch. It might also be useful to include another button to cycle through additional pre-programmed drone tunings not achievable on a real instrument; to activate an extra drone tuned a 5th above the baritone for example.

The regulator keys can easily be instrumented, either by mounting simple momentary switches in the holes they cover or by attaching wires directly to the keys themselves and allowing them to act as capacitive touch-plates. An alternative approach would be to use a position sensitive strip, like those used in some MIDI keyboards, for each regulator. This would allow for more flexibility of use – in standard operation the strips could be divided into zones corresponding to the various regulator keys, but an alternative mode could be implemented in software allowing the player to slide between notes or perhaps use regulator vibrato.

3.2 The Synthesis Model

In order to properly evaluate our interface, we will need a carefully designed synthesis model to drive with it. The subsections below review the synthesis possibilities that seem most appropriate for the chanter, drones and regulators.

3.2.1 Chanter Synthesis

The complex inter-relationships of the control parameters being measured here suggest a physical modelling approach as being the most appropriate during the initial evaluation of our electronic interface. This will involve tackling a number of difficult physical modelling issues, particularly in relation to the double reed excitation of the chanter. The following section offers a brief review of recent developments in the relevant areas of physical-modelling synthesis of woodwind instruments.

3.2.1.1 The Double Reed

Although the single reed of the clarinet and saxophone is well understood, the double reed remains something of a mystery. The two halves of the double reed run close to one another for a considerable distance near their tips, making Bernoulli forces become particularly important[5]. The flow resistance in the narrow staple also has a significant effect on its operation[6]. Josep Nebot reports some success with a CSound synthesis of the Grallot, a sort of double-reeded clarinet[7]. Cook (1995) has also conducted some research on the Aulos[8], a double-reed cylindrical-bore woodwind dating from the 5^{th} century BC, concluding that more theoretical and experimental work was required from the acoustics community before an accurate synthesis model of the double reed could be constructed. Guillaume Lemaitre, working in the Université du Maine and IRCAM, recently completed a masters thesis on a physical model of the oboe[9] and published a paper with Christophe Vergez, Xavier Rodet and René Caussé on the influence of bore conicity and the pipeneck downstream of a double reed[10]. They explain that the presence of the narrow pipe (or staple) causes a pressure drop between the top of the staple and opening of the conical bore, invalidating the flow model commonly used for the single reed, and propose a simple model for the pipeneck with the pressure drop represented by a discharge-loss coefficient. The resulting reed model exhibits three different behaviours depending on the discharge-loss coefficient chosen for the pipeneck.

3.2.1.2 The Conical Bore

The bore of the chanter is approximately a truncated straight sided cone with some subtle but significant deviations[11] which affect the alignment of the air column's modes of oscillation. For synthesis purposes, the chanter bore can be approximated as a serious of conic sections interspersed with tonehole scattering junctions.

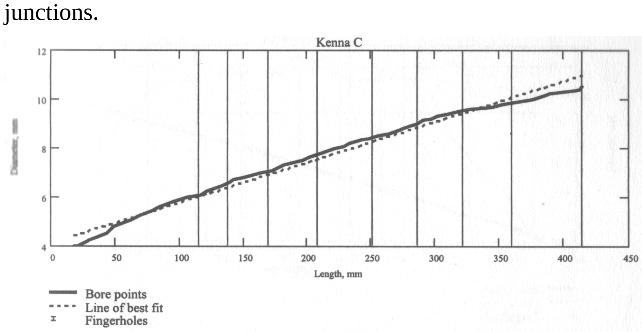


Figure 6: Bore Diameter vs. Distance for a Kenna chanter pitched in C[11]

Various previous studies have demonstrated the difficulty of establishing stable regimes of oscillation in a truncated conical bore. Scavone (2002) [12] presents a flexible model for such a bore and describes its implementation using digital waveguide techniques. In his doctoral thesis [13], on which our most recent work in this area has been based, Maarten Van Walstijn uses wave-digital filtering techniques to address some issues relating to the modelling of toneholes in a conical bore.

3.2.1.3 The Tonehole Model

Keefe (1981) [14] presented a study of woodwind tonehole providing distinct models for the open and closed toneholes. These models were translated for efficient digital waveguide implementation by Scavone and Smith[15]. In his doctoral thesis[16], Scavone presents a new tonehole model capable of dynamic state changes from fully-open through fully-closed. This latter solution does have a limitation on the minimum tonehole length (one spatial sampling interval) later addressed by van Walstijn and Scavone using wave-digital filtering techniques[17]. This wave-digital model, though more computationally complex than that presented in Scavone's thesis, is probably the most appropriate for our chanter model given the small diameter of some of the chanter toneholes.

3.2.1.4 Sound Radiation

Given that much of the dynamic variation in piping is achieved by opening and closing chanter toneholes, it will be important for us to accurately model the contribution of each tonehole to the overall sound radiated by the instrument. Scavone has dealt with this area in a paper on the modelling of wind instrument sound radiation in 3D space published in the proceedings of ICMC 1999, approximating each tonehole as an open-pipe discontinuity [18]. Lower frequency components tend to radiate in an almost omni-directional pattern while those at higher frequencies have greater magnitude in front of the pipe opening and along its axis. Scavone uses a frequency-dependent directivity filter for each radiation source to account for the angle between source and pickup-point. For our purposes it should be safe to assume that the observer is at a sufficient distance from the instrument that the angle to each source is approximately equal, allowing us to sum the pressure components contributed by each tonehole directly and avoid the additional computational complexity the inclusion of directivity filters would incur.

3.2.2 Drone Synthesis

A physical drone model would be similar to that of a simple clarinet and could be readily realised using digital waveguide techniques. As the drones are not "played" as such but rather tuned to the chanter at the outset and switched on and off as needed, a number of other synthesis approaches (additive, or even sample-based) could also be used interchangeably, or MIDI signals could be used to drive an external synthesis module.

3.2.3 Regulator Synthesis

The physical construction of the regulators would suggest a modification of the chanter synthesis model as being the ideal regulator synthesis solution. When we attend to the way in which they are played, however, it becomes clear that a much simpler and less computationally intensive solution will suffice. The regulators are key-operated, so a regulator tonehole may be held only in its fully-closed or fully-open state. This suggests that a simplified tonehole model will be adequate to the task. We can further simplify things when we consider that only one tonehole on each regulator will be open at any given time, suggesting that a model consisting of a double reed coupled to a conical, or even cylindrical, bore should be sufficient for our purposes. Indeed, as with the drones, the more mechanical way in which the regulators are played detracts from the benefits to be gained from a physical-modelling synthesis approach in terms of note transitions etc. The pitch corresponding to each regulator key is known, so the additive, sample-based and external synthesis options mentioned in the drone section above remain equally viable in this case.

4. CONCLUSIONS AND FUTURE WORK

In the course of the research described here, we have studied the Uilleann Pipes and the way in which they are played in an effort to identify the physical parameters that are manipulated by the player in their interaction with the instrument. On the strength of our findings we have come up with a design for a new electronic interface, at the core of which is a new tonehole-state sensing solution. We have successfully built two tonehole prototypes and written a Java interface allowing us to test them with physical models constructed using Perry Cook's Synthesis Toolkit (STK). Based on the design of the second of these prototypes, we have laid out the PCBs for an 8-tonehole electronic chanter. In preparation for the construction of a physically-based synthesis model with which to test our interface, we have reviewed much of the existing literature on the double reed and other relevant aspects of woodwind acoustics and physical modelling synthesis. Work has been begun on the implementation of the required building blocks within the framework provided by the STK.

Our observations suggest that the Uilleann Pipes have great potential as a basis for a new electronic musical controller. Their combination of expressive woodwind-style melodic control with the harmonic capabilities of the regulators should make them an attractive option in a performance context as well as a novel expressive MIDI controller. Our immediate goal is to complete construction of our physical interface. In parallel, we will be continuing to develop the physical synthesis model of the chanter discussed in section 3.2. Having verified our sensor arrangement using this synthesis model, the eventual goal is the abstraction of our interface through the development of a mapping layer which will allow us to drive arbitrary synthesis models using the EpipE controller.

5. ACKNOWLEDGEMENTS

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