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Chapter 2. McBlare: A Robotic Bagpipe Player

Roger B. Dannenberg, H. Ben Brown and Ron Lupish

Abstract McBlare is a robotic bagpipe player developed by the Robotics Institute and Computer Science Department at Carnegie Mellon University. This project has taught us some lessons about bagpipe playing and control that are not obvious from subjective human experience with bagpipes. From the artistic perspective, McBlare offers an interesting platform for virtuosic playing and interactive control. McBlare plays a standard set of bagpipes, using a custom air compressor to supply air and electromechanical “fingers” to control the chanter. McBlare is MIDI controlled, allowing for simple interfacing to a keyboard, computer, or hardware sequencer. The control mechanism exceeds the measured speed of expert human performers. McBlare can perform traditional bagpipe music as well as experimental computer-generated music. One characteristic of traditional bagpipe performance is the use of ornaments, or very rapid sequences of up to several notes inserted between longer melody notes. Using a collection of traditional bagpipe pieces as source material, McBlare can automatically discover typical ornaments from examples and insert ornaments into new melodic sequences. Recently, McBlare has been interfaced to control devices to allow non-traditional bagpipe music to be generated with real-time, continuous gestural control.

Roger B. Dannenberg

Computer Science Department, Carnegie Mellon University, e-mail: rbd@cs.cmu.edu

H. Ben Brown

Robotics Institute, Carnegie Mellon University

Ron Lupish

SMS Siemag

2.1 Introduction

In 2004, Carnegie Mellon University's Robotics Institute celebrated its twenty-fifth anniversary. In preparations for the event, it was suggested that the festivities should include a robotic bagpiper to acknowledge Carnegie Mellon's Scottish connection[1] using a Robotics theme. Members of the Robotics Institute set out to build a system that could play an ordinary, off-the-shelf traditional set of Highland Bagpipes with computer control. The system is now known as "McBlare".

Mechanized instruments and musical robots have been around for centuries. [8] Although early mechanical instruments were usually keyboard-oriented, many other electro-mechanical instruments have been constructed, including guitars and percussion instruments [9, 10, 13]. Robot players have also been constructed for wind instruments including the flute [11, 12] and trumpet [1, 14].

There have been at least two other robotic bagpipe projects. Ohta, Akita, and Ohtani [7] developed a bagpipe player and presented it at the 1993 International Computer Music Conference. In this player, conventional pipes are fitted to a specially constructed chamber rather than using the traditional bag. Their paper describes the belt-driven "finger" mechanism and suggests some basic parameters as a starting point for the design:

- 4 mm finger travel;
- 20 ms total time to open and close tone hole;
- 100 gf minimum closing force for tone holes.

Sergi Jorda also describes bagpipes used in his work, consisting of single pitched pipes that can only be turned on and off [4]. In a separate email communication, Jorda indicated that "Pressure is very tricky" and may depend on humidity, temperature and other factors. In contrast to previous efforts, the Carnegie Mellon project decided to use off-the-shelf bagpipes to retain the traditional bagpipe look and playing characteristics.

Additional basic information was obtained by meeting with Alasdair Gillies, CMU Director of Piping, and Patrick Regan, a professional piper. These experts were observed and videotaped to learn about the instrument and playing techniques. From slow-motion video (25% speed) the

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[1] Andrew Carnegie, who founded Carnegie Mellon (originally the Carnegie Institute of Technology), was born in Scotland. The University has an official tartan, the School of Music offers a degree in bagpipe performance, and one of the student ensembles is the pipe band.

fastest fingering appeared to be about 15 Hz. Required finger pressure on the chanter appeared to be very light. We noted breathing cycle periods of about 4 seconds, and measured the time to exhaust the air from the bag playing a low A: 12 seconds; and a high A: 8 seconds. (However, we now know that the lower pitches actually use a higher air flow at a given air pressure.) The numbers give a rough indication of the air flow requirement: between 0.045 and 0.07 cubic meters per minute (1.6 and 2.5 cubic feet per minute), based on a measured bag volume of 0.0093 cubic meters (0.33 cubic feet). Alasdair said he maintains a pressure of 32" water column (7.9 kPa or 1.15 PSI) in the bag. Soshi Iba, experienced piper and then PhD candidate in Robotics, also provided substantial input and served as a primary test subject, and the third author who joined the project later is also an accomplished piper.

The next section presents an overview of McBlare, beginning with a brief description of bagpipes and how they work. There are two major robotic components of McBlare: the air supply, and the chanter control, which are described in following sections. One of the major difficulties we encountered has been properly setting up the bagpipes and coaxing them into playing the full melodic range reliably. The final two sections report on our findings, current status, and some recent developments in interactive music control of McBlare.

2.2 Bagpipes

Bagpipes are some of the most ancient instruments, and they exist in almost all cultures. There are many variations, but the most famous type is the Highland Bagpipes (see Figure 2.1), and this is the type played by McBlare. There are three long, fixed pipes called drones. Two tenor drones are tuned to the same pitch, which is traditionally called A, but which is closer to B♭$_4$. The third drone (bass drone) sounds an octave lower. Drones each use a single reed, traditionally a tongue cut into a tube of cane, more recently a cane or artificial tongue attached to a hollow body of plastic or composite material. The fourth pipe is the chanter, or melody pipe. The chanter is louder than the drones and uses a double reed, similar in size to a bassoon reed, but shorter in length and substantially stiffer. Unlike a bassoon reed, however, it is constructed around a small copper tube, or “staple”.

Figure 2.1. Traditional Highland Bagpipes.

The chanter (lower left of Fig. 2.1) has sound holes that are opened and closed with the fingers, giving it a range from G_4 to A_5 (as written). All four pipes are inserted into the bag, a leather or synthetic air chamber that is inflated by the player's lung power through a fifth pipe, the blowstick or blowpipe (pointing to the upper left of Fig. 2.1). This tube has a one-way check-valve, so the player can take a breath while continuing to supply air to the reeds by squeezing the bag under his or her arm to regulate pressure.

Reeds at rest are slightly open, allowing air to pass through them. As pressure increases and air flow through the open reed increases in response, the Bernoulli effect decreases the pressure inside the reed, eventually causing the reed to close. The resulting loss of airflow reduces the pressure drop inside the reed, and the reed reopens. When things are working properly, the pressure fluctuations that drive the reed are reinforced by pressure waves reflected from the open end of the pipe, thus the oscillation frequency is controlled by the pipe length. The acoustic length of the chanter is mainly determined by the first open sound hole (i.e., the open sound hole nearest to the reed), allowing the player to control the pitch. For more technical details, see Guillemain's article on models of double-reed wind instruments [3].

It should be noted that the bagpipe player's lips are nowhere near the reeds of the bagpipe, unlike the oboe, bassoon, or clarinet. The bagpipe player's lips merely make a seal around the blowstick when inflating the bag. The reeds are at the ends of the four pipes where they enter the bag (see Fig. 2.1).

Pressure regulation is critical. It usually takes a bit more pressure to start the chanter oscillating (and more flow, since initially, the reeds are continuously open). This initial pressure tends to be around 8.3 kPa (1.2 pounds per square inch). Once started, the chanter operates from around 5.5 to 8.3 kPa (0.8 to 1.2 psi). The drone reeds take considerably less pressure to sound than does the chanter reed, and drones operate over a wider pressure range, so it is the chanter reed that determines the pressure required for the overall instrument. Unfortunately, the chanter tends to require lower pressure at lower pitches and higher pressure at higher pitches. At the low pitches, too high a pressure can cause the pitch to jump to the next octave or produce a warbling multiphonic effect (sometimes called “gurgling”). If insufficient pressure is maintained on the chanter reed for the higher pitches, it will cease vibrating (referred to as “choking”). Thus, there is a very narrow pressure range in which the full pitch range of the chanter is playable at a fixed pressure. Furthermore, pressure changes affect the chanter tuning (much more than the drones), so the chanter intonation can be fine-tuned with pressure changes. Typically, this is not done; rather, experienced pipers carefully attempt to adjust the stiffness and position of the reed in the chanter so as to be able to play the full 9-note range of the chanter with little or no pressure variation.

In some informal experiments, we monitored air pressure using an analog pressure gauge while an experienced player performed. We observed that air pressure fluctuated over a range from about 6.2 to 7.6 kPa (0.9 to 1.1 psi), with a tendency to use higher pressure in the upper register. Because of grace notes and some fast passages, it is impossible to change pressure with every note, and we speculate that players anticipate the range of notes and grace notes to be played in the near future and adjust pressure to optimize their sound and intonation.

Whether pressure should be constant or not is not well understood, although constant pressure is generally considered the ideal. For example, Andrew Lenz’s “bagpipejourney” web site described how to construct and use a water manometer. He says “Theoretically you should be playing all the notes at the same pressure, but it's not uncommon for people to blow harder on High-A [5].”

2.3 The McBlare Robot

From a scientific and engineering perspective, the main challenge of building a robot bagpipe player was lack of information. How critical is pressure regulation? How fast do “fingers” need to operate? Is constant pressure good enough, or does pressure need to change from low notes to high notes? Is a humidifier necessary? Building and operating McBlare has provided at least partial answers to these and other questions.

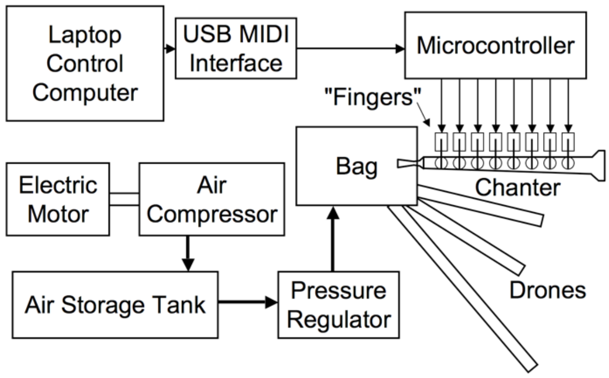

Figure 2.2 System diagram of McBlare.

Our bagpipe-playing robot, McBlare, uses a computer system to control electro-mechanical “fingers” that operate the chanter, and an air compressor and regulator to provide steady air pressure and flow to the bag. The system is diagramed in Figure 2.2. High-level control is provided via MIDI from a laptop computer (a MIDI keyboard may be substituted for direct control). MIDI is decoded by a microcontroller to drive 8 fingers (thus, McBlare has 8 degrees of freedom). The air supply uses a standard mechanical diaphragm-based pressure regulator and sends air to the bag via the blowstick. The pump is about 700mm wide, 300mm deep, and 400mm high. The chanter (a standard chanter) is about 330mm long (not counting the reed), and the minimum “finger” and tone hole spacing is about 19mm. The air supply and chanter control are describe in more detail below.

2.3.1 The Air Supply

McBlare uses a custom-built air compressor. A 1/16 HP, 115VAC electric motor drives a gearbox that reduces the speed to about 250 rpm. Two 76 mm (3”) diameter air pump cylinders, salvaged from compressors for inflatable rafts, are driven in opposition so that they deliver about 500 pump strokes per minute (see Figure 2.3). The radius of the crank arm driving the cylinders is adjustable from 15 mm to 51 mm (0.6” to 2.0”); we found that the smallest radius provides adequate air flow, calculated to be 0.034 cubic meters per minute (1.2 cubic feet per minute[2]). The air flow exhibits considerable fluctuation because of the pumping action of the cylinders. A small air storage tank sits between the pump and the pipes and helps to smooth the air pressure. Moreover, a high flow-rate, low pressure regulator drops the tank pressure of about 35 kPa (5 psi) down to a suitable bagpipe pressure. The pressure ripple on the bagpipe side of the regulator is a few percent with a frequency of about 8 Hz. This gives McBlare a barely audible “vibrato” that can be detected by listening carefully to sustained notes. The wavering pitch and amplitude might be eliminated with a rotary pump or a large storage tank, but the effect is so slight that even professional players rarely notice it.

Figure 2.3. The McBlare air compressor. Electric motor (not visible) drives eccentric (center) through a gearbox. Eccentric drives two air pump cylinders (right and left) in opposition.

The bagpipes are connected with a rubber hose that slips over the same tube that a human performer would blow into (the blowstick). By

[2] This is less than the 0.045-0.07 cubic meters per minute based on bag deflation measurements above. This may be due to differences in instruments and/or measurement errors.

blowing in air at a constant, regulated pressure, we can maintain pressure without squeezing the bag. (Earlier designs called for a mechanical "squeezer" but at 7 kPa (1 psi), a squeezer in contact with many square inches would have to be very powerful, adding significantly to McBlare's weight and complexity.)

Pressure regulation is adjusted manually using pump crank arm radius to control the rough flow rate, a bleed valve on the tank to relieve tank pressure that could stall the motor, and the pressure regulator. Fine adjustments are typically required using the pressure regulator to find the "sweet spot" where the lowest note sounds without gurgling and the highest note does not cut out.

The original reason to construct the pump was that such a powerful, low-pressure, high-volume pump is not readily available. The pistons were used rather than a rotary pump simply because they were available as salvage parts. After constructing the air compressor, we did locate an off-the-shelf rotary compressor that also works well, but is certainly not as fun to watch as the crank-and-cylinder pump.

2.3.2 The Chanter Control

The chanter requires "fingers" to open and close sound holes. Analysis of video indicates that bagpipers can play sequences of notes at rates up to around 25 notes per second. Human players can also uncover sound holes slowly or partially, using either an up-down motion or a sideways motion. The design for McBlare restricts "fingers" to up-and-down motion normal to the chanter surface. Fortunately, this is appropriate for traditional playing. The actuators operate faster than human muscles, allowing McBlare to exceed the speed of human pipers.

McBlare's "fingers" are modified electro-mechanical relays (see Figure 2.4). Small coils pull down a metal plate, which is spring loaded to return. Lightweight plastic tubes extend the metal plate about 3 cm, ending in small rubber circles designed to seal the sound hole. The length of travel at the sound hole is about 2.5 mm, and the actuators can switch to open or closed position in about 8 ms. The magnet coils consume about 1W each, enough to keep the mechanism warm, but not enough to require any special cooling. The magnet mechanism has the beneficial characteristic that the finger force is maximum (around 100 gf) with the magnet closed, the point at which finger force is needed for sealing the tone hole.

The whole "hand" assembly is designed to fit a standard chanter, but the individual finger units can be adjusted laterally (along the length of the chanter) and vertically. The lateral adjustment accommodates variations in hole spacing. The vertical adjustment is critical so that the magnet closure point corresponds to the point of finger closure.

The actuator current is controlled by power transistors, which in turn are controlled by a microcontroller. The microcontroller receives MIDI, decodes MIDI note-on messages to obtain pitch, and then uses a table lookup to determine the correct traditional fingering for that pitch. The full chromatic scale is decoded, although non-standard pitches are not in tune. MIDI notes outside of the bagpipe range are transposed up or down in octaves to fall inside the bagpipe range. Additional MIDI commands are decoded to allow individual finger control for non-standard fingerings. For example, an E will sound if the highest 3 tone holes (high A, high G, and F#) are closed and the E tone hole is open. The standard fingering also closes the D, C#, and B and opens the low A tone holes, but in fact, any of the 16 combinations of these 4 lowest tone holes can be used to play an E. Each combination has a subtle effect on the exact pitch and tone quality.

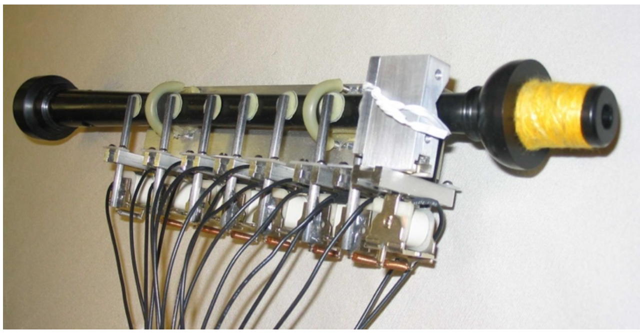

Figure 2.4. Chanter is mounted on aluminum block along with electromagnetic coils that open and close sound holes using rubber pads at the end of lightweight plastic tubes.

Grace notes, which are fast notes played between the notes of a melody (see “Ornamentation,” below), are traditionally played by simply lifting one finger when possible, taking advantage of alternate fingerings, but since McBlare has very fast and precisely coordinated “fingers,” we use standard fingerings for all notes including grace notes. In principle, we could send special MIDI commands to control individual fingers to achieve the same fingerings used by human pipers.

2.4 McBlare in Practice

McBlare is supported by a lightweight tripod that folds (see Figure 2.5) and the entire robot fits into a special airline-approved case for the pump and a suitcase for the remainder, making travel at least manageable. The chanter control works extremely well. The speed allows for authentic-sounding grace notes and some very exciting computer-generated sequences. The maximum measured rate is 16ms per up/down finger cycle, which allows 125 notes per second in the worst case. The chanter control is also compact, with the mechanism attached directly to and supported by the chanter.

We developed a small laptop-based program to play useful sequences for tuning and pressure adjustment. The user can then select and play a tune from a MIDI file. The program can also record sequences from a keyboard and add ornamentation as described below.

Figure 2.5. McBlare ready for performance.

As might be expected, there is considerable mechanical noise generated by the air compressor. In addition, the electro-mechanical chanter “fingers” make clicking sounds. However, the chanter is quite loud, and few people notice the noise once the chanter begins to play! We attempted to quantify this with a sound level meter. At 1m, McBlare generates an SPL of about 102dB outdoors, whereas the pump alone generates about 76dB. Thus, the pump noise is about 26dB down from the continuous bagpipe sounds. The bagpipe SPL varies a few dB with direction, pitch, and perhaps phasing among the drones, so this should be taken only as a rough estimate.

In our original work, we reported difficulty covering the full range of pitches from G_4 to A_5 [2]. More recently, we have found that the combination of good pressure regulation, eliminating even the slightest leak from closed tone holes, and a good reed (all three being critical) enable good performance across the full pitch range. A method to humidify the air has been strongly suggested by a number of bagpipe players. Although we have tried various approaches, we have been unable to achieve any solid improvements by raising the humidity, supporting a conclusion that humidity is at most of secondary importance after pressure regulation, the reeds, and sealing the tone holes. It should be noted, however, that humidity is hard to control and study, so we cannot rule out the importance of humidity. In particular, we suspect that humidity might affect the timbral quality of the chanter. Note also that another category of bagpipe is played by bellows and hence is not subject to the naturally humid breath of player, indicating that “dry” playing is at least in the realm of “normal” bagpipe playing. The adjustment of reeds to play well and reliably in the resulting dry environment is the subject of much discussion. Perhaps McBlare can someday serve as a testbed for comparing reeds in dry vs. humid playing conditions.

2.4.1 Ornamentation

The use of quick flourishes of notes (“grace notes”) between longer notes of a melody (ornamentation) is a characteristic of bagpipe music. Without ornaments, all bagpipe tunes would be completely “legato,” lacking any strong rhythm. In particular, if a melody contains two or more repeated notes, ornamentation is essential: since the chanter never stops sounding, there is no other way to signal a separation between the two notes. Ornaments are also used for rhythmic emphasis.

There are some basic principles used for ornamenting traditional highland bagpipe tunes, so a hand-coded, rule-based approach might allow ornaments to be added automatically to a given melody. Instead, we have implemented a simple case-based approach using a small database of existing bagpipe melodies in standard MIDI file format, complete with ornaments. Typical ornament sequences are automatically extracted from the database and then inserted into new melodies using the following procedure.

The first step is to build a collection of typical ornaments. Ornaments are defined as a sequence of one or more notes with durations less than 0.1s bounded by two “melody” notes with durations greater than 0.1s. A table is constructed indexed by the pitches of the two longer, or “melody” notes. For example, there is one entry in the table for the pair (E_4, D_4). In this entry are all of the ornaments found between melody pitches E_4 and D_4. The database itself comes from standard MIDI files of bagpipe performances collected from the Web. These appear to be mostly produced by music editing software, although actual recordings from MIDI chanters could be used instead.

The second step uses the table to obtain ornaments for a new, unornamented melody. For each note in the melody (except for the last), the pitch of the note and the following note are used to find an entry in the table. If no entry is found, no ornaments are generated. If an entry exists, then it will be a list of ornaments. An element of the list, which is a sequence of short notes, is chosen at random. The melody note is shortened by the length of the ornament sequence (something that human players do automatically to maintain the rhythm) and the ornament notes are inserted between the melody note and the next note.

There are many obvious variations on this approach. For example, the ornament could be chosen based also on the length of the melody note so that perhaps shorter ornaments would be chosen for shorter notes. One option in our system is to choose ornaments of maximal length to exaggerate the ornamentation. (In traditional practice, longer ornaments, or “doublings,” are often used to create a stronger rhythmic emphasis.)

2.4.2 Gestural Control

The use of MIDI control makes it possible to adapt all sorts of controllers to McBlare, including keyboards (which are very useful for experimentation), novel sensors, or even MIDI bagpipe controllers [6]. In our exploration of robot performance practice with McBlare, we wrote real-time software to enable the pipes to be played using a Nintendo Wii game controller (see Figure 2.6). The Wii controller contains a 3-axis accelerometer and a variety of buttons. The accelerometers can sense rapid acceleration in any direction. Because gravitation provides an absolute reference, the Wii controller can also sense orientation in 2 dimensions: left to right rotation (roll) and up to down rotation (elevation). The Wii controller provides multiple degrees of freedom, discrete buttons as well as continuous controls, wireless operation, and low cost, but certainly other controllers and interfaces could be developed.

One mode of control uses orientation to provide two parameters to a music generation algorithm. The roll axis controls note density, and the elevation axis controls interval size. The generation algorithm creates notes that fall on equally spaced rhythmic boundaries. At every boundary, a new note is generated with a probability determined by the roll parameter. As the controller is rotated clockwise from left to right, the probability of a new note increases, so the density of notes increases. At the extreme ranges of roll, the tempo is slowly decreased or increased. Each new note has a pitch determined as a random offset from the current pitch. The random offset is scaled by the elevation axis so that larger intervals tend to be generated with higher elevation. (Of course, the next pitch is also limited to the fixed range of the bagpipes.) This gives the user (performer) the ability to create and control a variety of melodic textures at virtuosic speeds.

After each new note is generated in this mode, we automatically insert ornamentation as described in the previous section. The ornamentation adds to the virtuosity and gives the performance a more idiomatic character.

Figure 6. McBlare operated by the first author using a Nintendo Wii controller.

A second mode of operation simply maps the elevation to pitch, allowing the user to run up and down scales and even play melodies in a "theremin-like" manner.

Finally, a third mode integrates the side-to-side acceleration sensor and maps the integral to pitch. The integral is clamped to a minimum and maximum to keep it in range. This allows pitch change to be directed by the user and correlated closely to the user's gestures. In addition, rotating the controller slightly right or left (the roll axis) will bias the accelerometer positively or negatively with gravity, causing the integral (and pitch) to drift upward or downward, respectively. There is no absolute position reference, so this mode does not allow the user to play a specific melody with any accuracy.

Buttons on the controller allow the performer to switch modes at any time. The combination of modes gives the performer access to a variety of musical textures and mappings of physical gesture to control. Although this control is not suitable for traditional music (and it is hard to imagine a better interface for traditional bagpipe music than human fingers and tone holes), the approach does offer new modes of music generation and interaction that would be extremely difficult or impossible using traditional means.

2.5 Conclusion & Future Work

McBlare is interesting for both scientific and artistic reasons. From the scientific perspective, McBlare allows for careful study of the behavior of bagpipes. For example, we have found that there is a very narrow range of pressure that allows the chanter to play its full range properly. This would explain the tendency for pipers to boost the pressure slightly for higher notes, but it also confirms the possibility of playing with constant pressure as advocated by expert players. McBlare offers a controlled environment for examining the effects of reed adjustments, humidity, and adjustments to tone holes. We have also recorded McBlare's chanter playing all 256 possible fingerings. Further analysis of these recordings may uncover some interesting new timbral and microtonal opportunities for bagpipe players.

Artistically, McBlare (and robotic instruments in general) offers a way for computers to generate or control music without loudspeakers. The threedimensional radiation patterns of acoustic instruments, the sheer loudness of highland bagpipes, and visibility of the means of sound production are important differences between McBlare and sound synthesis combined with loudspeakers. Aside from these physical differences, there is something about robotic instruments that captures the imagination in a way that must be experienced to be appreciated. The human fascination with automatons and the ancient tradition of bagpipes combine powerfully in McBlare, which has been featured not only in concerts but as a museum installation. Interactive control of McBlare leads to a unique and fascinating instrument.

One obvious difference between McBlare and human pipers is that humans can use their arms to rapidly apply pressure to the bag to start the pipes singing and release the pressure quickly to stop. McBlare, on the other hand, takes time to build up pressure. The chanter typically will not start until the optimum pressure is reached, but a chanter that is not in oscillation offers less air resistance, which in turn causes a pressure drop. The pressure drop inhibits the chanter from starting. This feedback process makes the bagpipes somewhat unstable and reluctant to start: until the chanter starts sounding, the lowered pressure will inhibit the chanter from starting. Usually, the (human) McBlare operator intervenes and speeds up the process by temporarily raising the system pressure until the chanter starts. At this point, one or more drones might be overblowing and need to be manually restarted. This all takes less than a minute, but is something a human can accomplish in seconds.

A more advanced system might sense when the chanter is sounding and automatically raise the pressure to restart the chanter when it stops. One could then go even further by automatically adjusting the pressure to eliminate “gurgling” on low notes (pressure is too high) or stopping vibration on high notes (pressure is too low). Since all of this would add weight and complexity, we will probably keep McBlare in its current configuration.

Bagpipes and drums are a traditional combination, and we plan to work on a robotic drum to play along with McBlare. With computer control, hyper-virtuosic pieces, complex rhythms, and super-human coordination will be possible. Examples include playing 11 notes in the time of 13 drum beats or speeding up the drums while simultaneously slowing down the bagpipes, ending together in phase. In order to explore the musical possibilities, we hope to create a website where composers can upload standard MIDI files for McBlare. We will then record performances and post them for everyone to enjoy.

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