AN INTELLIGENT SYSTEM MODEL OF THE PIANO TUNER

JACK SAUNDERS, ALAN BATTERSBY, DAVID AL-DABASS

School of Computing & Technology
The Nottingham Trent University
Nottingham, NG1 4BU.
alan.battersby@ntu.ac.uk

Abstract: Until now, all attempts at trying to automate the task of tuning a piano scale have relied largely on trying to provide a "one-fits –all" solution, the aim of which is to impart a superficial "appearance" of equal temperament. This is achieved by tuning the scale to an electronically generated perfect equally tempered template scale, adjusted or "stretched" by some arbitrary amount and then simply hoping for the best. This does not usually result in a scale that would fulfil the requirements of those "expert listeners" who are capable of judging the quality of such a scale.

A new approach to the problem of tuning of piano scales will be investigated here that involves the use of artificial intelligence (fuzzy logic) to determine a set of tuning corrections in the form of hard numerical data. The reason for trying this approach is to try to replace the "one-fits-all" solution with a tailor-made one that emulates the way that a human tuner tackles the problem. The rules that human tuners use have been well proven over many years, the use of which in a computerised system could well improve on the results so far achieved by the use of the equally tempered semitone system as described above. The earlier approach is the equivalent in fuzzy logic terms of a "crisp" or "non-fuzzy" method.

1. INTRODUCTION

Some background knowledge of the equally tempered scale will aid the reader in understanding the problems that are being addressed here.

Such information can be found in the standard treatments of the subject that are recommended reading for student/apprentice piano tuners e.g. those by [Braid-White] and [Samuel Wolfenden].

An appreciation of the background to relevant issues in the digital signal processing aspects of the project, i.e. Fourier Analysis of raw audio signal data in the form WAV files, can be obtained from sources provided by [Prof. F. dePiero] of CalPoly State University as well as the web site of [SIGVIEW] to name but a few.

The outcome of this endeavour is a comparison between fuzzy and non-fuzzy determination of scale corrections and concludes that the fuzzy method is the more accurate and sensitive of the two.

At the time of writing, the project has not as yet reached the stage where the efficacy of the system has been demonstrated on a real piano in a practical situation. The principle idea though has been demonstrated to produce credible results on data acquired from a real piano.

2. THE RATIONALE AND CHALLENGE FOR CHANGE

No matter what the "experts" may claim, the accuracy of the human auditory system is subject to severe limitations.

A well-known psycho-acoustic phenomenon is the inability of the human ear to distinguish quiet sounds from any louder sounds that are being simultaneously generated. This is a problem in piano tuning where the tuner is attempting to distinguish beats between say two beating quiet harmonics over a loud-sounding fundamental. Certain combinations of piano characteristics and ambient acoustics can make this a difficult task.
A good automated tuning system could make execution of this task a good deal easier.

An example of this would be trying to detect the beats generated by a scale fifth e.g. the beat rate for the F33-C40 fifth is only 0.59 beats/sec making its presence difficult to detect aurally. This order of beat rate is detected more skeletally rather than heard aurally and can be a major source of error. A good electronic note analyser system that would a part of any good automated system, could be very useful here.

Who uses tuning devices at the moment?

This is largely an American industry where the cowboy dominates (pun intended). There have been many warnings issued by professional piano tuning bodies in the UK that a tuner who turns up a your door and proceeds to tune your piano with any sort of electronic tuning device is probably deaf and should be shown the door! This may be something of an over-reaction, but in light of the fact that there is no "really accurate" tuning device as yet in existence, this could well represent sensible advice at this moment in time.

Another reason for being cautious when confronted with this situation is that there are no accredited piano technology courses available in the UK, Germany or elsewhere that certify its students on the basis of an examination tuning performed using a machine – electronic or otherwise. The tuning establishment simply views the use of such machines in private practice as "unprofessional" and unworthy of a qualified professional.

The use of equipment which uses simple equally tempered semitones is however often observed in factory situations at the stage of manufacture where tension is being applied to all the wires (initially at zero tension, i.e. "hanging loose") and ending up with a very uneven "rough" tuning at full tension, the aim of which is to stabilise the tuning state of the instrument at this final tension. This practice is also common in Japan and South Korea where there are large mass-producers of pianos. The accepted normal procedure is to "chip-up" the piano manually and level the string tension only as far as a rough tuning using the machine. A senior tuner then "fine-tunes" the piano, usually over several sessions before the piano finally leaves the factory. This process can take a year or more at quality makers such as Steinway and Bösendorfer. The piano is then subsequently fine-tuned by the retailer for demonstration in the showroom and then again at the location where the piano will finally be played by the end-user. At this stage the tuning stability will not be at its maximum, a situation that can take several years in some cases to achieve.

In several years there may well be no such thing as an acoustic piano available to buy anyway. It hasn't happened yet, but some day the fully digital piano will dominate the market and the acoustic piano will become a museum piece. To date this has not happened because the digital piano cannot as yet quite compete with the acoustic piano in the control over the sound produced that the latter offers to the player. Progress though in this field is relentless as in other areas where digital technology has emerged as the dominating technology.

Direct sensory feedback control over the sound produced by the piano though, is especially important to the professional concert pianist.

3. An AI APPROACH TO THE PROBLEM

Can the job be cut down to size?

Since the approach to be taken here is one of fuzzy logic, it would be beneficial to consider the position as regards the likely size of the rule base and the number of required inputs to the system.

Cutting down on the number of inputs will result in a simpler and thus more efficient rule base, therefore an analysis of what minimum level of input data information would be feasible would seem appropriate here.

The relationship between all the notes of the scale is the Cartesian product of all possible ordered pairs of notes in the scale as in **equation 1**.

Equation 1: all possible ordered pairs

Èn_k:Note„33 <= k <=45 ¦(n_iÀn_j)

i.e. there exists a relation called AllPossibleScaleIntervals where AllPossibleScaleIntervals**:Note¥ Note**

Not all pairs of notes are used however when tuning (solving) a scale aurally. In particular, semi-tonal intervals are not used with manual tuning methods, since the human ear is very restricted in its ability to detect small semi-tonal width distances of less than say 10 cents.

This order of pitch difference is crucial though in order to be able to realise a scale tuning temperament. These pitch differences are in practice indirectly accessed by listening to beats generated by three main groups of intervals – namely thirds fourths and fifths and sometimes sixths and minor thirds. Beats themselves are generated by the phase differences of the corresponding partials of the notes of which the intervals are comprised.

The number of ways that any two notes can be selected from 13 is given by the formula for combinations **equation 2** which is:

equation 2: no of possible selections

$$_{13}C_2 = \frac{13!}{2! * (13-2)!} = \frac{13 * 12}{2} = 78$$

The number of all possible ordered pairs of semi-tonal intervals (which are not used for tuning anyway) can therefore safely be removed from the set of all intervals where:

#{AllPossibleScaleIntervals} =78 **and**
{AllUsedScaleIntervals}={AllPossibleScaleIntervals}Œ{AllUnusedScaleIntervals}

where AllUsedScaleIntervals, AllUnusedIntervals are also relations of type
`Note¥ Note`
and #{`AllUsedScaleIntervals`} = #{`AllPossibleScaleIntervals`} **-** #{`AllUnusedScaleIntervals`}

There is an important reduction that can be made available here in the size of the set of intervals to be used when devising an algorithm that uses useful scale intervals.

The total reduction here is 50 intervals made up as follows from:

augmented fourths	7	never used for tuning
augmented fifths	5	never used for tuning
major sevenths	2	never used for tuning
minor sevenths	3	never used for tuning
minor thirds	10	including F33-G#36 (but see *)
semitones	12	never used for tuning
tones (two s/tones)	11	never used for tuning

This leaves 78-50=28 intervals which are used in tuning the scale made up as follows:

major thirds	9	always used for tuning
major fourths	8	always used for tuning
major fifths	6	always used for tuning
major sixths	4	sometimes used for tuning
octave	1	always used for tuning

In descending order of usefulness thirds, fourths and fifths remain as the most useful intervals to analyse in manual tuning. Major sixths/thirds are sometimes also used for redundancy checking, so these are not removed. This ranking is a personal view and it could be argued that rankings other than the latter could also be usefully used.

* It is also true that one of the 10 minor thirds mentioned above - namely the interval F33-G#36, is used occasionally as a secondary check for the octave F33-F45 by ensuring that the beat rates of the intervals F33-G#36 and G#36-F45 are equal; so one could argue that this interval should not really be removed from the set of all possible intervals.

An initial decision was made to eliminate all interval types other than thirds and fourths for use in the computerised system. This will cut down the number of intervals required from a maximum of 78 to only 18, made up as shown in **Table 1**:

The reason not to use fifths was taken for the following reasons:

Practical experience shows that scale errors are most easily spotted using fourths initially and then examining the two consecutive thirds included within the width of the fourth. e.g. the fourth F#34-C#41 includes the two consecutive thirds F#34-A#38 and G#36-C#41, the lower note of the lower third and the highest note of the higher third making the fourth. Fifths are largely used only as a secondary check in any case.

In practice it is a good idea to examine even good fourths for location of possible errors in the two included thirds – this is a powerful method of spotting hidden scale errors and will be of use in the computerised system. in the form of chunked data implemented as the “Included Thirds Algorithm”. This approach is also consistent with the philosophy which underpins Fuzzy Logic in the sense that the fuzzy rule base is an expression of established expert practice.

Table 1: minimum intervals required

Octave	F33-F45 1	
Thirds	F33-A37	
		F#34-A#38
		G35-B39
		G#36-C40
		A37-C#41
		A#38-D42
		B39-D#43
		C40-E44
	9	C#41-F45
Fourths		F33-A#38
		F#34-B39
		G35-C40
		G#36-C#41
		A37-D42
		A#38-D#43
		B39-E44
		C40-F458
	8	
Total		**18**

Using thirds and fourths in this way should reduce the role of the fifth and thus make its role redundant in the computerised system. Fifths will work out

OK anyway as long as all scale errors are correctly diagnosed using thirds and fourths.

It may even be possible eliminate the use of the fourth altogether in the computerised system thus cutting down the number of intervals used from 18 to 10, but whether or not this is feasible will depend on the effectiveness of the error solving algorithm in practice.

The fact that thirds and fourths are both tempered wide, whereas fifths are tempered narrow, further encourages and supports the rationale for algorithm simplification by using only thirds and fourths.

4. SOFTWARE DEVELOPMENT

Development and testing of Software

Three main programs were developed as follows:

A program to act as a provider of ***Equal Temperament Data*** developed in C++. This took the form of an abstraction of a piano, tuneable to any reference pitch and provides information on the width of any interval on the keyboard plus the pitches of all first five harmonics of any note on the keyboard. This proved indispensable when verifying note harmonics data during the development of the MATLAB scale analysis software.

A program to record scale data in the form of thirteen WAV files. The program has the capability of displaying the harmonics of any recorded note and can also store and analyse interval details from the scale. The capability of this program also extends to being able to provide details of any necessary corrections required to improve the scale error state. Two main functions were included in this program., one which implements a non-fuzzy logic solution and another which implements a fuzzy logic solution for finding scale correction moves. Another fuzzy inference system is then used to determine if the results of any implemented corrections can be regarded as acceptable. This program was implemented under the MATLAB non-GUI workspace environment.

A third program was also developed in C++ for the purpose of obtaining the harmonic analysis of any recorded note, but it was instead decided in the course of software development to incorporate this functionality into the MATLAB program referred to above.

Details of the development of the Equal Temperament Piano Abstraction

This was implemented as a C++ DOS console program using the Microsoft Visual C++ V6. compiler and I.D.E.

The basic design of this program was based on the method that a human tuner uses to tune any piano; i.e. start by tuning A49 to the selected reference pitch, tune the scale to this pitch and then copy the scale outwards from the scale in both directions along the keyboard from left to right. The fundamental harmonic of each note relates to its adjacent notes in the ratio of the twelfth root of 2. The scale object is implemented as a linked list of note objects. After the scale object has been created, this is then passed as a parameter to the function which builds the full keyboard compass (also implemented as a linked list of notes). This keyboard object is then instantiated and is then used as the main data structure from which note and interval data from the whole piano can be accessed and analysed. An advantage of passing the scale object as a parameter is that the program could easily be adapted to take other types of scale e.g. Werckmeister or Mean Tone if ever required.

Figure 1 which follows shows the main menu for the piano abstraction program.

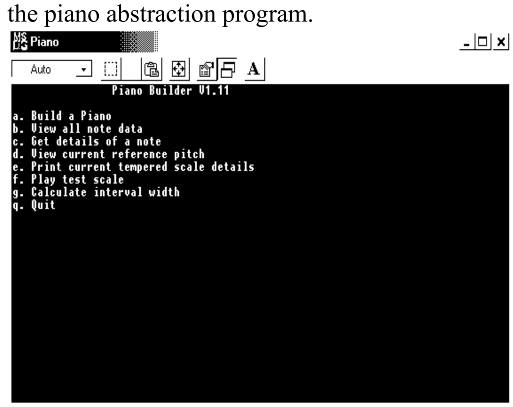

Figure 1: screenshot of Piano V1.11 main menu

Fuzzy logic calculation of scale corrections

To facilitate comparison of both fuzzy and non-fuzzy methods of scale corrections, another FIS was developed to calculate scale correction suggestions. This was implemented as a Mamdani type called “evalchunk.fis” and has a rule base as shown in **Figure 2.**

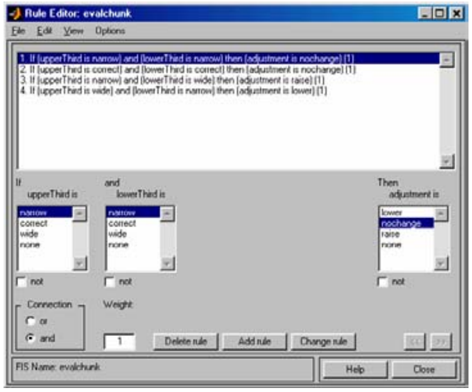

Figure 2: rules for scale corrections in "evalchunk" FIS

This FIS takes the width of a two adjacent thirds (the two "included thirds" of a fourth) and supplies these as inputs to the FIS whose output is a measure of the correction required to improve the widths of both thirds (if required). This is another way of implementing the "included thirds algorithm" but this time using fuzzy logic.

5. RESULTS AND DISCUSSION

Figure 3 shows the result of the fuzzy analysis of the tempered scale.

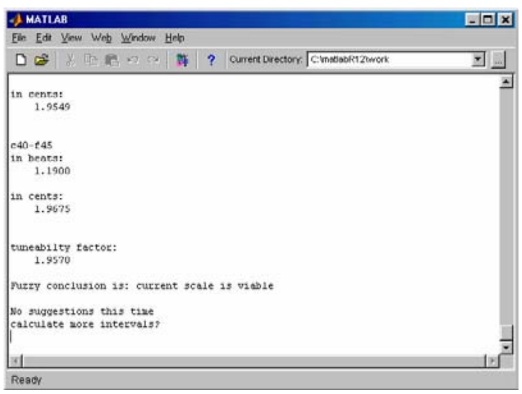

Figure 3: Fuzzy analysis of tempered scale using data from tempered.mat

The result in **Figure 4** shows unsuppressed output which would not normally be seen. The program has correctly determined that the scale is viable and that only insignificant corrections are required due to round-off errors in the original tempered scale calculation.

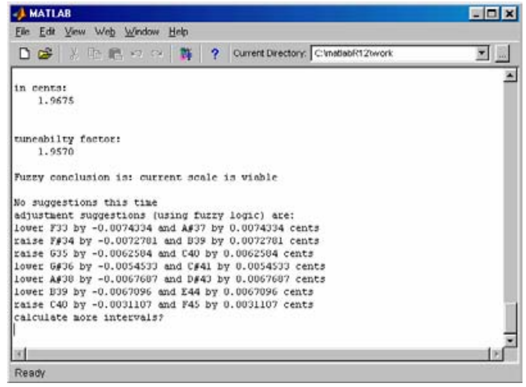

Figure 4: unsuppressed display of results for tempered.mat using fuzzy logic

Figure 5 shows results from a scale whose data was acquired from a real piano. The output shows a scale which is non-viable and also the corrections which would be required on a first iteration.

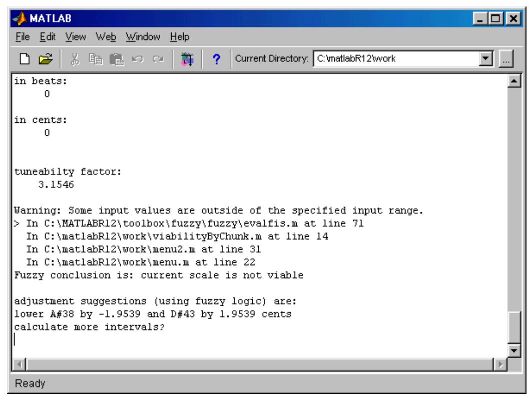

Figure 5

6. CONCLUSIONS

The project succeeded to the extent that a basis for the original concept has been established as previously stated i.e. to implement the ability to measure scale data, determine its viability and suggest hard numerical correction data using Fuzzy Logic that could be supplied to an electro-mechanical or pneumatic device that could actually set the tuning.

The ability of the system to supply this data is the core requirement of an automated system. If nothing else, the capability of being able to offer an opinion as to the error state of the scale is in itself a useful aspect for the training and examining students of piano tuning .

This use of fuzzy logic in this context corresponds with established ideas on its use in areas where it is difficult to implement code that can accurately emulate the expertise of a human expert. The use of fuzzy logic for piano tuning seems to be an ideal solution to the problem and in the end may prove to be the only feasible way of automating piano tuning at all.

This project has only dealt with the implementation of the system up to the point where it supplies the fuzzy correction data and has not examined the last part, i.e. the one that involves the design of the hardware/software for the mechanical tuning device. This aspect of the system would make an interesting research topic in itself.

REFERENCES

F.dePiero, Dept of Electrical Engineering CalPoly State University. *Example code for WAV file I/O.* See main dissertation.
http://www.ee.calpoly.edu/~fdepiero/fdepiero_dsp_software/dsp_software.html

Gabriel Weinreich, part of a series of five lectures on the acoustics of the piano for the *Royal Swedish Academy of Music.* Lecture title: 'Mistuned Strings'. 1990. These lectures are now disseminated on the Internet and can be found at:
http://www.speech.kth.se/music/5_lectures/weinreic/mistuned.html
See main dissertation.

Website for Werckmeister III historical keyboard temperament information, Well-Tempered scales etc. Updated 2002, Author's name is unknown
http://www.kirnberger.fsnet.co.uk/Charts

William Braid-White, 'Piano tuning and Allied Arts' *Published by American Piano Supply Co.* (Out of Print) For many years the accepted textbook in many schools and libraries. This famous work by America's prominent author, teacher, and technician is one every tuner, however skilled, should read and re-read to learn more fully the details of the craft. Available from *Heckschers* at :
http://www.uk-piano.org/heckscher/hec_book.html

Samuel S. Wolfenden, 'A Treatise on the Art of Pianoforte Construction' Published in 1977 by Unwin Brothers Limited, Old Woking, Surrey, England. Contains useful material on the subject of Equal Temperament. Regarded as a standard textbook on the subject. Available from *Heckschers* at:
http://www.uk-piano.org/heckscher/hec_book.html

BIOGRAPHY

Jack Saunders is a qualified piano tuner with over 30 years of experience in this field. An interest in computing combined with a particular interest in the theory of piano tuning/scale temperaments gained over this period has resulted in the findings presented in this paper. Programming know-how stems from a combination of self–taught and university-acquired knowledge of C++ and MATLAB. (The Nottingham Trent University). The project is still in its infancy and several major hurdles have yet to be overcome. Hopefully the solutions to these problems will be discovered in the course of on-going research.