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Published in:
Proceedings of the New Interfaces for Musical Expression 2020 conference

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kiefer, C., Overholt, D., & Eldridge, A. (2020). Shaping the behaviour of feedback instruments with complexity-controlled gain dynamics. In *Proceedings of the New Interfaces for Musical Expression 2020 conference* (pp. 343-348) https://www.nime.org/proceedings/2020/nime2020_paper66.pdf

Shaping the behaviour of feedback instruments with complexity-controlled gain dynamics

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ABSTRACT

Feedback instruments offer radical new ways of engaging with instrument design and musicianship. They are defined by recurrent circulation of signals through the instrument, which give the instrument 'a life of its own' and a 'stimulating uncontrollability'. Arguably, the most interesting musical behaviour in these instruments happens when their dynamic complexity is maximised, without falling into saturating feedback. It is often challenging to keep the instrument in this zone; this research looks at algorithmic ways to manage the behaviour of feedback loops in order to make feedback instruments more playable and musical; to expand and maintain the 'sweet spot'. We propose a solution that manages gain dynamics based on measurement of complexity, using a realtime implementation of the Effort to Compress algorithm. The system was evaluated with four musicians, each of whom have different variations of string-based feedback instruments, following an autobiographical design approach. Qualitative feedback was gathered, showing that the system was successful in modifying the behaviour of these instruments to allow easier access to edge transition zones, sometimes at the expense of losing some of the more compelling dynamics of the instruments. The basic efficacy of the system is evidenced by descriptive audio analysis. This paper is accompanied by a dataset of sounds collected during the study, and the open source software that was written to support the research.

Author Keywords

complexity, feedback musicianship, augmented instruments

CCS Concepts

•**Applied computing** → **Sound and music computing;**
•**Human-centered computing** → **User studies;**

1. INTRODUCTION

Musical practice with feedback instruments is fundamentally concerned with negotiating a path between control and uncontrol. Often, feedback instruments are at their most *musical* when these elements are balanced; however the zone where this occurs can be difficult to guide or push the instrument into, and challenging to maintain. We propose a new algorithm, *CoFlo* (COmplexity-controlled dynamics in the Feedback LOop), which addresses this issue.

Feedback instruments are characterised by the recurrent circulation of signals, leading to non-linear and complex dynamical behaviours [4]. These dynamics create characteristic sonic outputs, and also mean that the more-or-less stable sensory-motor contingencies which underpin mastery of and performance with traditional instruments dissolve: there are dynamic, often unpredictable, rather than fixed relationships between physical gestures and sonic outcomes; they possess a 'stimulating uncontrollability' [18]. Currently we can observe busy research and artistic activity in this area (e.g. [8, 15, 13, 2] and many more).

The problem of keeping feedback instruments in a playable zone is articulated by Eliane Radigue, an early pioneer of this musical practice: *'you only had a hairbreadth to play with.'* [7]. Mudd et. al further describe these zones as where *edge interactions* occur, characterised by emergent and unpredictable behaviours, and the risk of abrupt changes, including failure [9] .

When playing with feedback instruments, we differentiate two types of feedback; desirable feedback, which lends the instruments interesting and unpredictable musical dynamics, and unwanted feedback, which causes the instrument to become less responsive, and is usually characterised by a strong dominant resonant frequency and harmonics which this frequency excites. In complex systems terms, the instrument has fallen into a strong basin of attraction, and it's hard or impossible to pull the instrument back to a more musical mode of behaviour without damping it or starting again from silence. We can call this *saturating feedback* as it dominates the sound and playability of the instrument.

Our proposed algorithm is designed to prevent saturating feedback from occurring, while retaining the rich musical dynamics of the edge interactions. It builds upon the observation that a saturating feedback signal is less complex than the unsaturated sound of the instrument: Saturating feedback is characterised by a dominant resonant frequency and quieter harmonics; this is less complex than either (a) the natural sound of an acoustic instrument or (b) the feedback-actuated instrument when not saturated, which exhibits complex micro *and* macro behaviours, shifting between attractors rather than falling into them. CoFlo uses a measure of complexity, Effort To Compress (ETC) [10] to monitor the sound circulating in the feedback loop. Based on the assumption that saturated feedback exhibits a reduced complexity, ETC is used as a control signal to manage overall system gain, such that it damps the feedback loop to prevent saturation.

This class of closed-loop feedback system is already used

NIME'20, July 21-25, 2020, Royal Birmingham Conservatoire, Birmingham City University, Birmingham, United Kingdom.

outside of musical applications, for example for drug administration based on realtime complexity of EEG signals [5]. In audio related applications we see feedback suppression techniques based on adaptive audio filtering, for example as applied in hearing technologies [14]. In these applications, feedback is ameliorated to keep an audio system in a linear mode of functioning; in contrast CoFlo aims to maximise the potential for nonlinear and complex dynamics generated by feedback, without the system become saturated. Research in the NIME field has also explored the use and algorithmic control of feedback in active acoustics and augmented instruments [1, 17, 16]. To the best of our knowledge, this is the first time that realtime measurement of complexity has been used to modulate the dynamical behaviour of feedback instruments. The aim of the study presented here was to implement a real-time complexity measure and investigate the musical effect and experience of its application in shaping the behaviour of feedback instruments; in future work we envisage carrying out a more systematic, comparative analysis to establish if there are more optimal algorithms and implementations.

The software we created for this study is open source; this paper is also accompanied by a dataset of recorded example sounds and the Jupyter notebook we created for data analysis.

2. METHOD

The study involved three phases: 1) software implementation of a real-time complexity measure, Effort to Compress (ETC) 2) musical experimentation in case studies with four different feedback instruments and players; and 3) qualitative analyses of resultant acoustic responses of the instruments and musical experiences of the players.

2.1 Effort To Compress

Effort To Compress is a complexity metric that has been shown to be more effective for short and noisy time series than measures such as Shannon entropy and Lempel-Ziv [10], making it ideal for monitoring a short sliding window in realtime audio applications. It uses a lossless compression algorithm: Non-Sequential Recursive Pair Substitution (NSRPS), and is defined as the number of iterations for NSRPS to transform a signal into a constant sequence. It works as follows, on a vector of discrete symbols **x**:

```
1: function ETC(x)
2:     etc=0
3:     Find p, the most frequently occurring non-overlapping pair of symbols in x
4:     Replace all occurrences of p in x with a new symbol
5:     $etc = etc + 1$
6:     Measure the shannon entropy $s$ of x
7:     if $s > 1e^{-6}$ or $|x| > 1$ then return to line 3
8:     etc = etc/(|x|-1)
9: end function
```

The result will always be between 0 and 1.

CoFlo is optimised for realtime analysis of audio signals using ETC. ETC could be calculated for any feature of an audio signal, in this context we used RMS loudness. It is calculated as follows (in equation 1):

$$\mathbf{w} = \sum_{j=0,\delta,2\delta\ldots}^{m-1} \left(\sqrt{\sum_{i_{rms}=j}^{n-1} \mathbf{x}^2_{i_{rms}}} \right) \tag{1}$$

x is a buffer of recent values of the live audio signal being analysed; n is the RMS window size; β is the RMS hop size m is the window size for ETC analysis. **w** is therefore a vector of RMS values.

$$etc\_rt(\mathbf{w}) = ETC\left(\left\lfloor \frac{\mathbf{w}}{max(\mathbf{w})} \cdot \gamma \right\rfloor \right) \tag{2}$$

Equation 2 describes the discretisation and analysis of the RMS window. γ is the maximum number of discrete symbols presented to the ETC analysis, and v is the resulting ETC value. v is calculated every η steps, where a step is a new value of **w**.

2.2 Gain Control

CoFlo implements proportional gain control, as a response to changes in ETC, with configurable responsiveness and effect strength (as shown in equation 3).

$$\begin{aligned} s &= min(1.0, ((1.0 - etc\_rt(\mathbf{w}))\alpha)^{\varphi}) \\ g &= LPF\,(input : 1.0 - s, frequency : \lambda) \\ y &= g \sum_{i=0}^{ch-1} input_i \cdot gain_i \end{aligned} \tag{3}$$

ETC is used to create a feedback system to manage instrument gains, akin to a Watt governor, keeping the instrument on the edge of feedback, between saturation and silence. The ETC value is calculated per buffer on the incoming audio signal then inverted and multiplied by a damping factor α (range $[0, 10]$). The resultant response curve is adjusted by exponent φ in the range $[0.5, 3.0]$ to tune sensitivity to small values. To calculate gain, the result is inverted again, and fed to a biquad low-pass filter, parameterised with frequency λ and resonance 0.1, which determines the response speed of the system.

2.3 Implementation

Software for this research[1] was made in C++ and OpenFrameworks. The software was placed in the feedback loop of each instrument, by taking one or more inputs and returning a single output, with dynamics managed by the CoFlo algorithm. The software ran with a 64 sample buffer size (at 44.1kHz sample rate) to minimise any delay in the feedback loop. For two of the case study instruments (see below), sound examples were recorded for analysis. The default settings were: $n : 64, \beta : 32, m : 50, \eta : 25, \gamma : 8, \alpha : 1, \varphi : 1, \lambda : 1.5Hz$; settings are specified below where different. All parameters were available for realtime adjustment by the player.

2.4 Case studies

In order to gain insights into the effects of the algorithm, CoFlo evaluation was carried out by 4 different players on four different feedback instrument (see figure 1): a new adaptation of the Overtone Fiddle [12], two variants of the Feedback Cello [4], and the Halldorophone [18].

2.4.1 The Overtone Fiddle

The Overtone Fiddle [12] is an instrument originally developed in 2010, which incorporates physical actuation of the acoustic body via embedded tactile sound transducers. These create responsive vibrations in both main and secondary bodies, originally incorporating only DSP effects that can be driven into the primary body without excessive amounts of feedback. As with all instruments included in this study, such tactile sound transducers allow for performer control and sensation via both traditional instrumental techniques, as well as extended playing techniques that

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[1] `https://github.com/chriskiefer/liveCCC`

incorporate shared human/machine control of the resulting hybrid electronic/acoustic sounds.

2.4.2 *Feedback Cellos*

Feedback Cellos [4] are augmentations to traditional acoustic cellos; pickups are mounted under each string, the signals summed and sent to a speaker built into the rear of the instrument, causing it to self-resonate. Sound from the strings is externally processed and amplified back into the cello body. Kiefer's instrument has two extra exciters and the gains are controlled digitally; Eldridge's has two additional drone strings beneath the bridge and gains are managed with analogue circuits. Kiefer and Eldridge have been performing with and modifying their instruments since building them in 2016. Sound examples were recorded from Kiefer's instrument for analysis. Each player explored the algorithm on their own instrument and reflected on their experience.

2.4.3 *The Halldorophone*

The halldorophone [18] is a cello-like feedback instrument, on which the design of the above Feedback Cellos were based. The variant used in this case study had an inbuilt amplifier and speaker, four stoppable strings, two fixed pitch sympathetic strings, and individual pickups on each string. Four instrument-mounted sliders control the gain on the stoppable strings.

The participant was an experienced musician, but relatively new to the halldorophone and feedback instruments.

2.4.4 *Procedure*

Evaluation of user experience was approached according to autobiographical design methods (ABD) [11]. ABD has been demonstrated as a successful method for investigating self-usage of technology [3]. This method was adopted for two reasons: to ensure an open-ended approach at the early stages of the design of a new system, and to capture personal perspectives on the new method, through the lens of the authors' own idiosyncratic instruments, which they each have deep, long-term experiences of playing with and developing. The advantages and potential pitfalls of this approach are explored in the discussion section.

Kiefer and Overholt's reflections are based on the development of CoFlo over a two month period at Aalborg University, Copenhagen, during which they tested and refined it with their two instruments, and also elicited further feedback through frequent demonstration and dialogue with other musicians. Eldridge co-developed the theoretical research behind the algorithm; her reflections are based on a 90 minute session with CoFlo at the end of the development period. The halldorophone player experimented with CoFlo during a 30 minute session, following a three week period exploring the naked halldorophone.

Audio recordings were inspected visually using spectrographic displays in order to establish the impact on the algorithm on the acoustic response of each instrument. The accompanying dataset and analysis notebooks are available online[2].

3. RESULTS

3.1 Case study 1: The Overtone Fiddle

We begin by illustrating behaviour under different conditions in the Overtone Fiddle, to demonstrate basic CoFlo function.

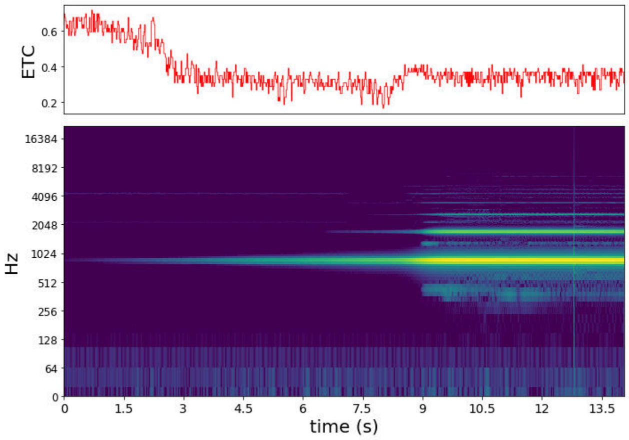

Figure 2: Overtone Fiddle with no damping

In figure 2, the instrument is left to feedback with no intervention ($\alpha = 0$). A single resonant frequency becomes increasingly louder, until it induces harmonics. ETC drops as the feedback frequency builds, and then rises again when the harmonics are induced.

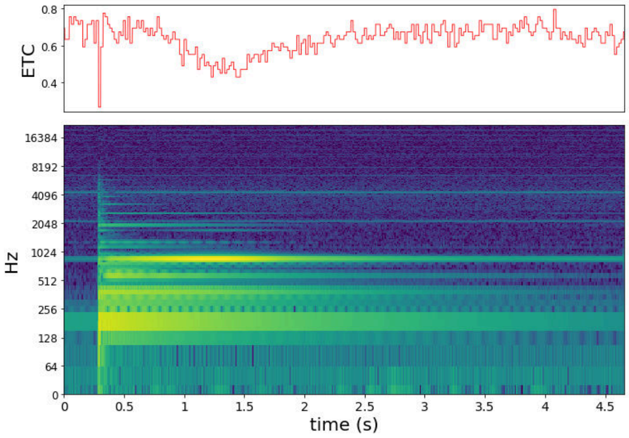

Figure 3: Overtone fiddle with damping

Figure 3 shows the damped violin, with $\alpha = 2.4$. Open strings are hit to induce a tone, and feedback starts to build at a frequency just below 1024Hz. As this builds, the ETC value drops, and CoFlo reduces the master gain so that the feedback is prevented.

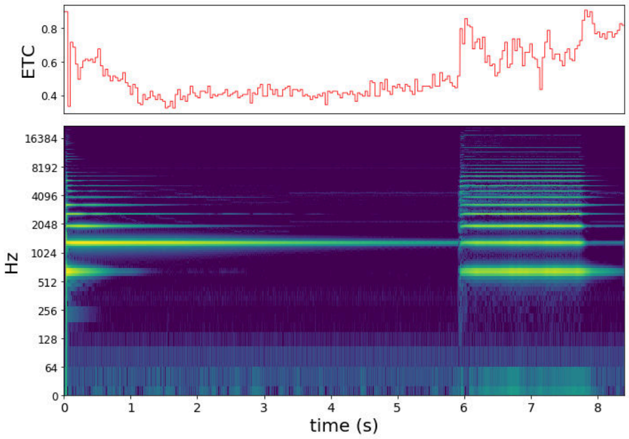

Figure 4: Overtone fiddle string I, feedback vs bowing

Figure 4 demonstrates how CoFlo detects feedback sounds but ignores bowing; the violin string I (with others damped)

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[2] `https://github.com/chriskiefer/Complexity-Gain-Dynamics-NIME2020_Data_Analysis`

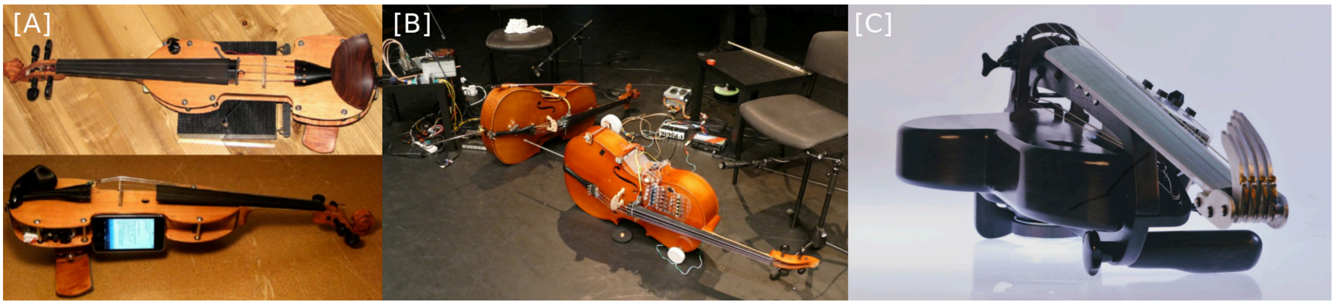

Figure 1: Case study instruments: [A] The Overtone Fiddle, [B] Feedback Cellos, [C] The Halldorophone

is perturbed and allowed to feed back, bringing the ETC reading to a low value, however when the string is bowed in the second audio event; the ETC value remains high. In this example a higher symbol count of $\gamma = 53$ was needed to respond to feedback at a higher pitch.

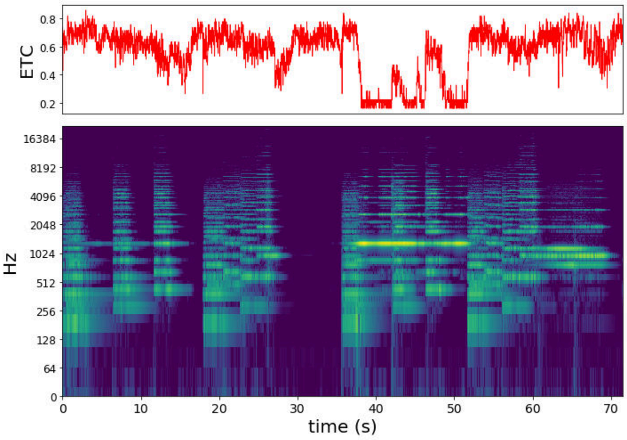

Figure 5: Overtone fiddle with reverb, with and without (after 30s) damping

Reverb is mixed in to the feedback loop in figure 5. This can be problematic because the set of filters in a reverb can act as strong resonant attractors and cause feedback. Before 30s ($\alpha = 3.9, \lambda = 4.7Hz$), the system manages to prevent feedback from occurring, while preserving the use of the effect. After 30s ($\alpha = 0$), the instrument is dominated by saturating feedback, further evidenced by the ETC value showing low complexity.

Overholt summarises his experience of using CoFlo with the Overtone Fiddle:

Previously unattainable DSP effects are possible with CoFlo. While only reverb was utilized in this study, it became immediately clear that such effects - having originally been avoided due to uncontrollable feedback in the primary body of the Overtone Fiddle - are possible to enjoy when using CoFlo. Reverb is clearly just one example, and it will be exciting to explore further with effects such as chorus, flanging, harmonizing, etc.

CoFlo allows newfound confidence. Good musical instruments act as extensions of the human body, and well-trained performers have said that it can feel like the instrument becomes a part of themselves. Losing control of the instrument entirely, which can (and does) happen with the Overtone fiddle (when not consciously avoiding feedback-inducing algorithms) breaks this connection and causes a loss of confidence. When properly setup - making sure all parameters are well "tuned" - CoFlo manages to entirely avoid this disconnect, allowing increased confidence while performing.

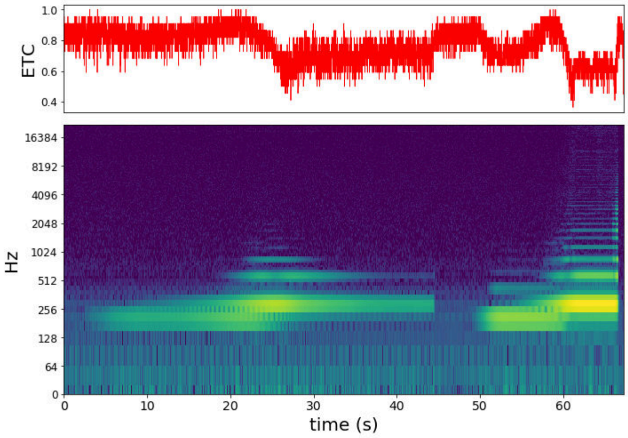

Figure 6: Feedback Cello with open strings, with and without (after 50s) damping

CoFlo can only be evaluated holistically. Overall, the impression of being 'on the edge of chaos' while playing is not something that can be shown in graphs, nor completely evaluated quantitatively. While useful to see and hear the results of CoFlo on various actuated and feedback instruments shown herein, there is no substitute for the embodied experience itself. A qualitative, holistic evaluation would elucidate further impressions, possibly via improvisations exploring the embodied interaction between performer and instrument.

3.2 Case study 2: The Feedback Cello

Visual inspection of spectrograms illustrates the impact of CoFlo on the acoustic dynamics of the feedback cello. Figure 6 provides a comparison of the behaviour of the raw feedback and with CoFlo . Open strings being left for feedback to build, initially with damping ($\alpha = 1.68$), and then without ($m = 23, \varphi = 1.34, \lambda = 2Hz$). With damping, we can see ETC dip as feedback builds, and in turn the gain is brought down to reduce the feedback. With no damping, the complexity dips, and the feedback builds continually.

Figure 7 demonstrates the difference in complexity between bowing and feedback ($m = 98, \lambda = 1.3Hz$). Between 0s and 10s, a stopped note is bowed, and then the bow is lifted so that feedback is allowed to build. Without damping, a resonant frequency becomes dominant, and the ETC value drops. This action is repeated, but with damping on; as the simplicity drops, gain management reduces the volume so the feedback dies away, the ETC value dips and then climbs reflecting this.

Kiefer reflects on his use of CoFlo as follows:

CoFlo allows a more reliable and deeper exploration of feedback dynamics, at the expense of some subdued behaviour. It becomes easier and more fluid to explore the details of the instrument without the risk of

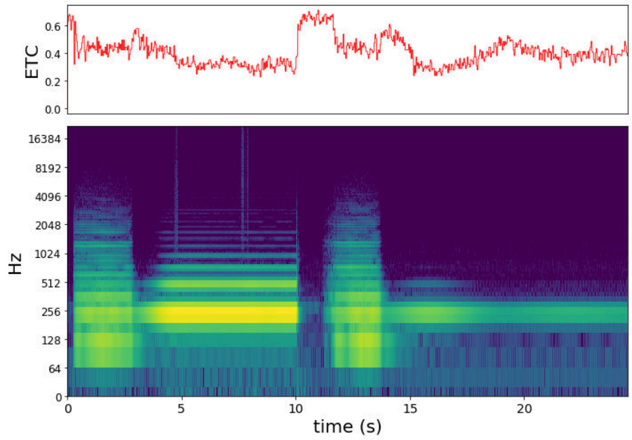

Figure 7: Feedback Cello, bowing a stopped string and then leaving feedback to build, without and with (after 11s) damping

saturation, The instrument feels less *wild* than normal, but in some ways it becomes more lively because you can push more energy into the feedback loop without it saturating. Some gestures become more repeatable, where this would be challenging otherwise. With more complex material, CoFlo moves beyond gain and feedback control and becomes a tangible effect in itself; it clearly changes the character of the instrument.

Tuning α and λ can be challenging. The damping factor isn't absolute, it works in a fine balance against the amplitude of the input. It would be best to set it as a parameter with a footpedal, so that it becomes a dynamic parameter for music exploration instead of a static parameter. Depending on λ, the system can go into coupled oscillation, as it dampens and un-dampens; this might be an undesirable effect.

Use of new effects becomes possible. The reverb used in the study would typically make the instrument difficult to play; CoFlo allows strong resonant frequencies to be added to the feedback loop without the instrument saturating, and while retaining musical dynamics.

Eldridge summarises her experience:

CoFlo fine tunes the dance of agency between instrument and player. Part of the allure of the feedback cello to me is its uncontrollability, there's a strong sense of working *with* another dynamical force when you are playing with it. But when saturating feedback occurs, it's like being pulled into a fast current in a boat with no sail, there's an inevitability that is uncontrollable in an uninteresting way. CoFlo feels like it provides a sail and with adjustable ropes. It's not that you have full control of the waters you're sailing in, but you are able to work *with* the feedback cello to steer into and through the rapids; it creates are more turbulent, less inevitable and more interesting experience.

CoFlo sensitises the couplings between strings. One thing I've noticed with the feedback cello is that it amplifies the couplings between cello strings. With this algorithm in play I can excite sympathetic resonances across strings in a more nuanced and way, and actually start to play with it musically. Without the system, hitting resonant frequencies on adjacent strings can derail you - now we can surf around different spaces without getting stuck.

3.3 Case study 3: The Halldorophone

The interview with the halldorophone player was transcribed and analysed. During the three week period of halldorophone use before the interview, they had themselves recognised the need to *"expand the sweet spot"* of the instrument, and had been experimenting with their own algorithms for this purpose. Interview analysis yielded the following key points:

CoFlo extends the controllabilty of the instrument *'I think what it does is it means you can get to more subtle resonances without them getting destroyed too quickly', 'it feels like this thing and this kind of more control thing is necessary to get it in a slightly more controllable space, [where] that sweet spot is wide'*

Continuous control of damping was desirable *'I would definitely like continuous control over that [CoFlo] to allow it to get to a point where ... it's on the edge', 'if you had [CoFlo] on a pedal,...you would eventually just forget about it and you'd just be riding it all of the time'*

The general response of the instrument is dampened *'[the sweet spot] it's wider and it's more normal, it sounds more like the instrument as it normally is and more like a normal cello as well, the acoustic aspects of how you're playing are more retained but the kind of craziness is more dampened', 'it's definitely more controllable, but that just means that bowing at some points is not that interesting , because the general bowing stuff that I found interesting was when you're activating some other part of the instrument'*

4. DISCUSSION

Our methodology combined autobiographical design with descriptive audio analysis and an interview with a new player. ADB reflections are given from the three authors who have been engaged in the design process of CoFlo. Research into ADB shows that it can reveal the major issues with a system, that it leverages long-term experience, and supports early innovation [11]; these factors fit well with this project, which involves the evaluation of a new system by designers who have long-term experience of their instruments. It is acknowledged that these accounts are subjective, and cannot form the basis for a generalised evaluation. We attempt to improve rigor by combining multiple accounts of use, including the halldorophone player who was new to the system, and by presenting descriptive audio analysis to show the functional impact of the system on the acoustic response of the instruments to recursive feedback. These results shed light on early use of CoFlo, providing a foundation for future research in this area.

Results from audio analysis reveal how ETC can differentiate between the sound of the instrument and the sound of saturated feedback, and show how CoFlo uses this data to modulate the gain in the feedback loop and prevent the system from falling into saturating feedback. These audio examples are from contrived scenarios that do not represent examples of musical play; they reveal basic efficacy and workings of the system, but do not necessarily illustrate the impact of the algorithm in more complex performance scenarios. For more detailed understandings, we look to qualitative accounts of player experience. Examining the four accounts of use, it's clear that CoFlo could significantly alter the dynamical behaviour of the case study instruments, creating a zone which is at once richer and more nuanced, and also 'safer', whilst preserving the quintessential liveliness of the instruments. It does this by dynamically adjusting the gain, steering the system away from the abyss of saturated feedback, keeping it in the 'rapids' of the edge zones; this in turn enables a more nuanced, expressive exploration of tonal dynamic details. The system also facilitates the use of a reverb effect that would have been otherwise challenging to use in a feedback loop. The cost of using this system was to lose some of the energy and wild response of the naked instrument. An obvious solution to preserve the best of both worlds would be to allow continuous control of CoFlo parameters, in particular the damping factor, α, via a footpedal.

CoFlo is pragmatically constrained by CPU power; realtime calculation of ETC is computationally expensive. Performance is difficult to improve through parallelisation, as the algorithm is recursive, and is further limited by the need for very small buffer sizes with feedback instruments. The software used in this research used roughly half of the power of a single i7 CPU. Unfortunately, for now, this precludes use with embedded systems, which would be ideal for instruments such as the halldorophone, that have on-board digital signal processing.

5. CONCLUSIONS AND FUTURE WORK

We have described the motivation, implementation, exploration and evaluation of CoFlo, a novel algorithm that can 'tune' feedback instruments into the zone of rich complexity 'on the edge'. To achieve this, the algorithm measures complexity in realtime using Effort To Compress, and modulates the gain of the system proportionally. It could be described as a *complexity compressor*, as it tries to maximise the potential for complex behaviour of a feedback instrument. Descriptive sound analysis illustrated the basic efficacy of the algorithm in two different instruments. The algorithm was evaluated qualitatively following an autobiographical design approach with three participants, and further evaluated through interviews by a new halldorophone player. The results show that for these players and instruments, CoFlo was able to change the behaviour of the instruments to reduce or prevent saturating feedback, and allow new modes of sonic exploration. For the time being these results are not necessarily generalisable beyond the instruments and players in the four case studies, but they do set up a basis for further exploration of this system. Future studies should assess this class of complexity-based dynamics control across the many and varied designers and players of feedback instruments. Our initial research highlights the value of further research in this area, including into a wider range of complexity metrics and audio features and optimisation of their parameters with real and synthetic audio materials. ETC is used as the basic measurement in a novel dynamical causality measurement [6] developed for neuroscientific research. Realtime versions of these metrics are also included our software library; they have promising applications in segmentation and analysis of audio in feedback systems.

6. ETHICAL STANDARDS

Data collection for this research carried out with ethical clearance, ref: ER/HU36/2.

7. REFERENCES

[1] E. Berdahl, J. O. Smith III, and G. Niemeyer. Feedback control of acoustic musical instruments: Collocated control using physical analogs. *The journal of the acoustical society of america*, 131(1):963–973, 2012.

[2] T. Davis. Instrumental intentionality: an exploration of mediated intentionality in musical improvisation. *International Journal of Performance Arts and Digital Media*, 15(1):70–83, 2019.

[3] A. Desjardins and A. Ball. Revealing tensions in autobiographical design in HCI. In *proceedings of the 2018 designing interactive systems conference*, pages 753–764, 2018.

[4] A. Eldridge and C. Kiefer. The self-resonating feedback cello: interfacing gestural and generative processes in improvised performance. *Proceedings of New Interfaces for Music Expression 2017*, 2017:25–29, 2017.

[5] W. M. Haddad, K. Y. Volyanskyy, J. M. Bailey, and J. J. Im. Neuroadaptive output feedback control for automated anesthesia with noisy eeg measurements. *IEEE Transactions on Control Systems Technology*, 19(2):311–326, 2010.

[6] A. Kathpalia and N. Nagaraj. Data-based intervention approach for complexity-causality measure. *PeerJ Computer Science*, 5:e196, 2019.

[7] K. Molleson. Interview: Eliane Radigue, 2018.

[8] T. Mudd. Between Chaotic Synthesis and Physical Modelling: Instrumentalising with Gutter Synthesis. In *Procedings of the Conference on Compuation, Communication, Aesthetics and X (xCoAx)*, pages 217–228, 2019.

[9] T. Mudd, S. Holland, and P. Mulholland. Nonlinear dynamical processes in musical interactions: Investigating the role of nonlinear dynamics in supporting surprise and exploration in interactions with digital musical instruments. *International Journal of Human-Computer Studies*, 128:27 – 40, 2019.

[10] N. Nagaraj, K. Balasubramanian, and S. Dey. A new complexity measure for time series analysis and classification. *The European Physical Journal Special Topics*, 222(3-4):847–860, 2013.

[11] C. Neustaedter and P. Sengers. Autobiographical design in hci research: designing and learning through use-it-yourself. In *Proceedings of the Designing Interactive Systems Conference*, pages 514–523, 2012.

[12] D. Overholt. The overtone fiddle: an actuated acoustic instrument. In *NIME*, volume 11, pages 4–7, 2011.

[13] D. Sanfilippo and A. Valle. Feedback systems: An analytical framework. *Computer Music Journal*, 37(2):12–27, 2013.

[14] H. Schepker, L. T. Tran, S. Nordholm, and S. Doclo. Improving adaptive feedback cancellation in hearing aids using an affine combination of filters. In *2016 IEEE International Conference on Acoustics, speech and Signal Processing (ICASSP)*, pages 231–235. IEEE, 2016.

[15] J. Snyder, R. Erramilli, and M. Mulshine. The Feedback Trombone: Controlling Feedback in Brass Instruments. In *New Interfaces For Musical Expression*, 2018.

[16] E. Thuillier, O. Lähdeoja, and V. Välimäki. Feedback control in an actuated acoustic guitar using frequency shifting. *Journal of the Audio Engineering Society*, 67(6):373–381, 2019.

[17] A. Van Troyer. Composing embodied sonic play experiences: Towards acoustic feedback ecology. In *NIME*, pages 118–121, 2014.

[18] H. Úlfarsson. Feedback Mayhem: Compositional affordances of the halldorophone discussed by its users. In *Proc. ICMC, New York*. 2019.