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ORIGINAL PAPER

Multisensory instrumental dynamics as an emergent paradigm for digital musical creation

A retrospective and prospective of haptic-audio creation with physical models

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Abstract

The nature of human/instrument interaction is a long-standing area of study, drawing interest from fields as diverse as philosophy, cognitive sciences, anthropology, human–computer-interaction, and artistic creation. In particular, the case of the interaction between performer and musical instrument provides an enticing framework for studying the instrumental dynamics that allow for embodiment, skill acquisition and virtuosity with (electro-)acoustical instruments, and questioning how such notions may be transferred into the realm of digital music technologies and virtual instruments. This paper offers a study of concepts and technologies allowing for instrumental dynamics with Digital Musical Instruments, through an analysis of haptic-audio creation centred on (a) theoretical and conceptual frameworks, (b) technological components—namely physical modelling techniques for the design of virtual mechanical systems and force-feedback technologies allowing mechanical coupling with them, and (c) a corpus of artistic works based on this approach. Through this retrospective, we argue that artistic works created in this field over the last 20 years—and those yet to come—may be of significant importance to the haptics community as new objects that question physicality, tangibility, and creativity from a fresh and rather singular angle. Following which, we discuss the convergence of efforts in this field, challenges still ahead, and the possible emergence of a new transdisciplinary community focused on multisensory digital art forms.

Keywords Physical modelling · Virtual musical instruments · Audio-Haptic · Artistic Creation

1 Introduction

The physical interaction that occurs between human and instrument (be it a musical instrument or otherwise) has been an important area of study over the last century, increasing the understanding we have of the human somato-sensorimotor system and leading to new theories and experimental studies regarding human cognitive processes. Over the last thirty years, the advent of human–computer interaction, virtual realities and numerical simulation has brought forward concurrent questions as to the interaction qualities between human and virtual environments.

Music constitutes a fascinating prism through which the above questions may be studied, providing both a rich canvas of expressive gestures and virtuosity amongst acoustical instrument performers, and a strong current reliance on digital processes and tools for musical expression. This, however, raises several fundamental questions such as:

> Can a digital musical instrument be considered an instrument, in the same way that an acoustical instrument is?
> Can (or should) interaction with a digital instrument allow for a comparable degree of expressiveness and similar potential for skill acquisition and virtuosity to those of an acoustical instrument?

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Such interrogations lead to considerations of bio-mechanics, cognition, technological systems and creative processes, resulting in the recent emergence of pluridisciplinary *Musical Haptics* communities [61]. Indeed, haptics provide a viewport through which physical interaction, including with virtual entities, may be observed. In particular, force-feedback technologies coupled with physical simulation techniques may allow for bidirectional, energy-based physical interaction with virtual musical instruments [45], resulting in a new category of digital musical instruments (DMIs), grounded on the analysis of human/musical instrument interaction as dynamically coupled systems, thus yielding *instrumental dynamics* in the digital context.

This paper discusses the use of such instruments within the scope of musical creation, drawing on conceptual and theoretical positions, technological aspects, and the analysis of a series of audio-haptic musical works. Through such an analysis, we hope to point out technological and conceptual convergences that may inform and help direct future efforts for the emergence of a new haptics community focused on multi-sensory musical and/or digital art forms.

2 The dynamics of performer-instrument interaction

The study of the interaction between a performer and a musical instrument relies strongly on theories of embodied cognition. The interaction between human and environment is considered as an interconnection of dynamical systems, coupled through action and perception channels. We develop knowledge both of the environment and of ourselves by acting upon the environment through various modalities (speech, sound, gesture) and having it act upon us in return.

Gestural interaction presents a singularity in this regard: while it may serve purely informational and communication purposes (described in Claude Cadoz's terminology as *epistemic* and *semiotic* functions [13,17]), it may also offer a closed action-perception loop between human and environment: Cadoz names this the *ergotic* function of *instrumental* communication. The ergotic function is the seat of dynamical exchange of physical energy between two physical systems (the user and environment), transforming both through energetic coupling. Cadoz argues that this energetic exchange between user and environment is key to expressive gestural interaction such as the one that occurs in dexterous manipulation of tools, or in gestures present in artistic creation.

In a recent position paper [59], O'Modhrain and Gillespie provide an in-depth analysis and model for the coupled dynamics of performer/musical instrument interaction, considering the dynamic coupling to be at the very essence of how we learn to master mechanical instruments. Their position is similar to Cadoz's model (cf. Fig. 1) of bidirectional

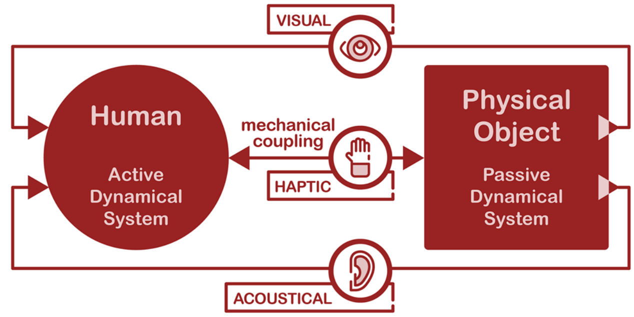

Fig. 1 The relationship between human and (possibly musical) instrument portrayed as two dynamically coupled systems, as depicted in the works of Cadoz and colleagues [13]

dynamic coupling (*"a musician both drives and is driven by their instrument"*) in that closing the sensory feedback loop results in the instrument becoming an extension of the body, thus the interface disappears as the player gains new means to interact with the environment.[1]

The model proposed in Fig. 1, in which the human is considered as a global dynamic energy source, is extended by considering the backdrivable bio-mechanics of the human body and disassociating a fast inner loop consisting of the dynamic coupling of the instrument interface and human bio-mechanics, and a slower outer loop including the central nervous system, through which the performer drives the inner loop dynamics (Fig. 2). They exemplify this phenomenon through musical gestures that exhibit oscillatory behaviours outside the scope of human volitional control, such as drum rolls, *spiccato* bowing or fast piano trills: in each of these cases, the musician does not provide muscle actions at the oscillation frequency, rather he/she modulates and synchronises driving action to obtain the desired oscillatory behaviour from the coupled bio-mechanics/instrument interface system. In short, O'Modhrain's claim is that

> the musician is not playing with the musical instrument but instead playing with the coupled dynamics of his or her own body and instrument

and that learning and mastering an (acoustical) instrument then consists in

> refining control of one's body, as extended by the musical instrument through dynamic coupling.

The above position poses a strong conceptual framework for analysing the design and nature of digital musical instruments in regards to their acoustical counterparts, and questioning their nature as *instruments*. This will be dis-

[1] This relates to André Leroi-Gourhan's definition of the "instrument" as a mechanical object used by man to perform a physical, morphological and functional adaptation between him/herself and the environment [49].

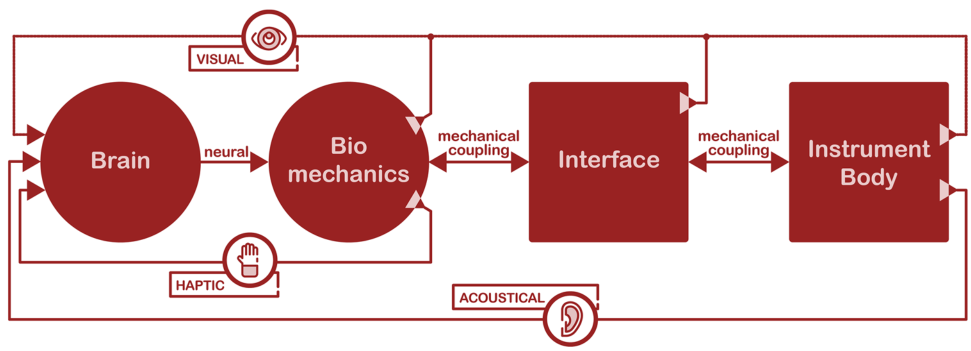

Fig. 2 The relationship between human and instrument modelled as an inner loop of coupled dynamics formed by the human bio-mechanics and the instrument's interface, driven by an outer loop including the central nervous system and motor intent, inspired by O'Modhrain and Gillespie's model [59]

cussed in the following section, with a specific interest in physical approaches to DMIs, enabling to instigate a certain degree of dynamic coupling through force-feedback technologies.

3 Designing digital musical instruments that exhibit instrumental dynamics

3.1 DMIs as sound control interfaces

Wanderley and Depalle [74] broadly define Digital Musical Instruments as systems allowing gestural control of sound production, composed of a gestural controller (typically featuring sensors and possibly actuators) whose features can be mapped to various sound production parameters. As such, DMIs are generally conceived as elaborate control systems interfacing gestural features to sound through freely-assigned arbitrary mappings—that is, the exchange from gesture to sound is purely informational and one-directional [51]. This architecture proves particularly useful in real-time control of arbitrary sound synthesis or transformation techniques, as the physical decoupling from gestural input to sound production unit transcends constraints of traditional (electro-) acoustical instruments. DMIs often provide passive haptic feedback through the morphology and design of the gestural controller (with the exception of mid-air controllers, such as motion tracking). While these ergonomics may prove useful for manipulating the device, they bear no relationship to the sound produced (with the exception of haptic DMIs, discussed hereafter).

The immense variety of DMIs [52,60] and their widespread study [53,57,75] and use in various musical contexts[2] are a testimony to their pertinence as creative devices. Their nature as *instruments* in the traditional sense has however raised questions [19], leading O'Modhrain to reject the dominant "control" paradigm and call for a new type of digital instrument, centred on haptic feedback and the mechanical dynamics of the instrument interface allowing for dynamic coupling with the human bio-mechanical system [59].

Designing digital instruments that trade control authority and information systems for physical interaction, motor intent and impedance matching is no simple affair, particularly from a technological standpoint. On the one hand, creating a digital instrument capable of storing, transforming and returning physical energy through an interface calls for (sometimes complex) physical modelling techniques, while, on the other hand, developing force-feedback interfaces that allow intimate and high-bandwidth dynamic coupling with virtual resonating bodies is, to this day, a tricky and demanding technical challenge. Below, we present various concepts and works that aim to restore notions of physicality, or indeed instrumental dynamics, into DMIs.

3.2 Physical approaches to DMI design

The incorporation of haptic technologies is now fairly commonplace in digital musical instruments (be it through vibrotactile actuation or force-feedback devices), with motivations ranging from employing the haptic channel to provide additional information to the user [32] (as auditory and visual channels are heavily solicited in musical practice), to using haptic guidance to help perform musical gestures [33], or allowing for physical interaction with part, or all, of a virtual musical instrument [44,56,66]. Our interest lies in the latter case.

3.2.1 Distributed haptic digital musical instruments

A common practice in designing haptic DMIs is to distribute various components of the instrument or virtual scene into separate computational processes for each modality (Fig. 3a). The user interacts with a local mechanical model that represents the instrument interface. Information from the interaction with this model is then used to drive arbitrary sound-synthesis processes, using classic mapping strategies. Examples include Nichols' *vBow* friction-driven haptic interface [56], Gillespie's *Virtual Piano Action* [30], Bill Verplank's *The Plank* [72], or the *Dimple* software [67].

[2] As displayed by the New Instruments for Musical Expression (NIME) community: https://www.nime.org/.

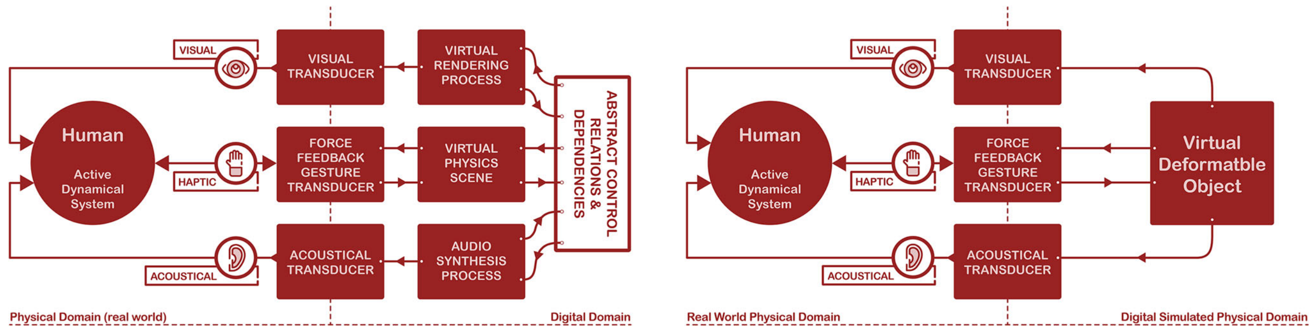

Fig. 3 **a** Distributed (left) and **b** Unitary or *multisensory* (right) approaches to Haptic Digital Musical Instruments

Decoupled models for visual, haptic and sound modalities allow for flexible and generally asynchronous processing of the scene: visual rendering is handled at a relatively low rate (50–100 Hz, latency of up to 40 ms), audio is processed at a high-rate (44.1 kHz, with latency under 10 ms), and physics are generally computed around 1kHz, with critical latency conditions for the haptic loop (1 ms or less).

This approach is an extension of the classic DMI architecture and proves especially adapted in cases where audio or visual processes may rely on abstract (non-physical) algorithms. However, it does pose the problem of defining mapping and control relationships between the processes. If the temporal and/or conceptual correlation between different modalities is not sufficiently explicit, the sensation of believability and presence of the virtual instrument may suffer [25]. It follows that although they may allow for exchange of potential and kinetic energy between the body and a local (non-acoustical) virtual mechanical interface, systems designed in this way do not provide haptic cues on the energetic aspects of the sound process and do not instigate bidirectional coupling from gesture to sound. They are therefore only a partial solution to designing DMIs that allow for instrumental dynamics.

3.2.2 Unitary haptic digital musical instruments

If one desires to create virtual musical instruments that maintain complete energetic coherence, the only option is to design them entirely using physical modelling techniques so as to haptically couple the user to a *unitary* or *multisensory* model that exhibits visual, mechanical and acoustical behaviour (Fig. 3b). The object that is touched is the one seen and heard, with guaranteed coherence between the different modalities.

With the exception of technical limitations, virtual instruments conceived this way adhere to the principles of dynamic coupling stated by O'Modhrain, and should therefore allow for comparable playability, skill development and transfer to those at play in acoustical instruments. Several experimental results conducted on high-performance force-feedback systems [28] tend to confirm this hypothesis [37,46,50,66].

In the following section, we discuss technological considerations for both design and simulation of virtual mechanical instruments, and force-feedback technologies enabling direct interaction with them.

4 DMIs with instrumental dynamics: technological aspects

Designing digital musical instruments that exhibit the qualities of instrumental dynamics demands two major technological elements: physical modelling techniques to conceive and simulate virtual mechanical systems and force-feedback technologies that enable physical interaction with them.

One may broadly define physical modelling techniques as frameworks in which virtual objects or scenes may be designed as one or several systems, whose computed dynamical behaviour obey some type of physical laws, such as Newtonian mechanics, fluid dynamics, quantum mechanics, etc. Simulation techniques rely on computational means to represent bidirectional physical coupling—for instance by solving partial difference equations for system dynamics, or performing closed loop calculations on dual state variables such as *force* and *position*. In the case of virtual musical instruments, Newtonian mechanical dynamics generally form the basis for physical modelling techniques, several of which are presented below.

Force-feedback systems work in a similar fashion, by coupling position and force data by means of sensors and actuators to enable interaction with virtual dynamical systems (typically physical models of some sort or another). Devices strive for the lowest closed-loop feedback latency between the two in order to maintain numerical stability and to allow for dynamic exchange of energy (which in the case of musical instruments can cover the entire audio bandwidth). See [35] for a comprehensive review of force-feedback concepts and devices.

4.1 Physically-based virtual musical instruments

4.1.1 Physics-based sound synthesis

The first works into modelling and simulating acoustical behaviours can be attributed to Hiller and Ruiz [38] in 1971, proposing finite difference schemes for the 1D wave equation allowing to simulate physical string vibrations. Cadoz, Florens and Luciani then proposed the CORDIS system [16], a lumped element modelling paradigm and a first modular formalism for modelling and simulating virtual objects by a point-based mechanics representation—often called *mass interaction* or simply *mass spring* networks—which will be detailed below. The 80s and 90s saw the rise of modal synthesis, and also waveguide models [69] that became widely accepted in the academic circles and offered significant improvement of computation cost by computationally representing physical waves as digital delay lines. In recent years, finite difference schemes for acoustical simulation [12] have gained enormously in popularity, due in part to significant improvements in computing power, opening the possibility for real-time synthesis.

4.1.2 Mass-interaction physical modelling

Representing real-world mechanical systems by means of punctual masses linked together by elements such as springs or dampers and submitted to various external forces or constraints is one of the most common ways to calculate and analyse their behaviour. From Newton's laws we know the equation of movement of a mass in a given referential; the action of springs, dampers and other elements can be mathematically described or approximated by well known formulas. Resolving the equation system composed of the equations of each element in a mechanical construction gives the global behaviour.

Mass-interaction physical modelling and simulation relies on exactly this principle: the inertial behaviours of material elements and interactions (springs, dampers, etc.) are described by simple discrete-time difference equations [41], following certain discretisation schemes—see [55] for an in-depth analysis. Physical models are then built by assembling masses and interactions together into a network, setting physical parameters and initial conditions, and then computing behaviour over time (see Fig. 4 for a simple example). Positions and forces can be expressed as scalar values (for 1D systems) or as 2D or 3D vectors according to the spatial attributes of the scene. In the case of virtual musical instruments, this allows modelling both general purpose mechanical attributes (which may be two or three-dimensional) and aero-acoustical vibratory sections (often modelled as one-dimensional).

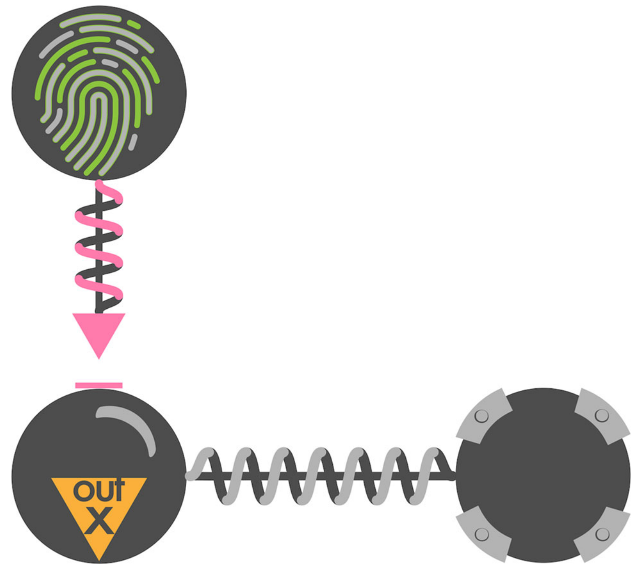

Fig. 4 A mass/spring/fixed-point resonator (bottom) struck by another mass (top). Kinetic energy from the top mass is transferred into potential energy in the resonator mass during collision, resulting in oscillatory motion (i.e. synthesising a pure harmonic tone)

Owing to their inherent simplicity and relatively efficient computation, lumped methods such as mass-interaction physics have been widely used and studied in the field of haptics for the design of virtual deformable matter and haptic interaction models [20,54], including for direct force-feedback interaction with virtual musical instruments [5,45]. Hence, the majority of artistic works presented hereafter are based on mass-interaction modelling and simulation tools.

4.1.3 A brief history of mass-interaction tools for musical creation

CORDIS- ANIMA [14] can be considered the original mass-interaction physical modelling formalism, coming into existence in its prototypical form at ACROE as soon as the early eighties, including pioneering views as to the potential of coupling with force-feedback technologies [16,26]. It forms the basis for MIMESIS, an environment for 3D physical modelling destined for animation, and GENESIS, an environment for physical modelling sound synthesis based on 1D mass-interaction networks - both of which are off-line modelling and simulation tools providing advanced user interfaces for designing complex mass-interaction physical models.

Following years saw the emergence of several direct variations on CORDIS- ANIMA, providing open implementations for sound synthesis in the form of TAO [62], PMPD's integration into Pure Data [36], or CYMATIC, a tool allowing for model design and real-time force-feedback interaction [39].

A third wave of mass-interaction tools have appeared in the last decade, driven by open-source initiatives: HSP (hap-

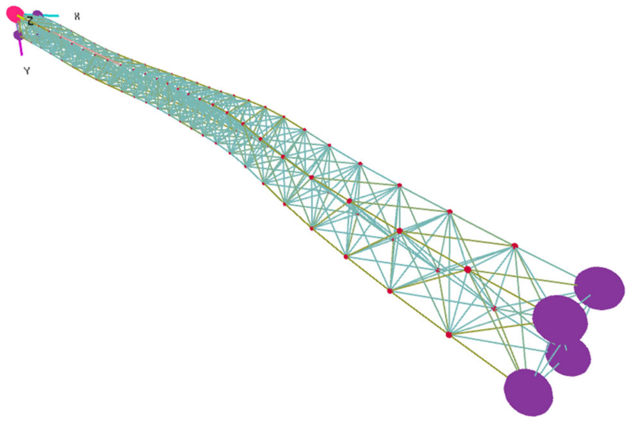

Fig. 5 3D mass-interaction model of a beam designed and simulated for sound synthesis with the MIPHYSICS engine [73]

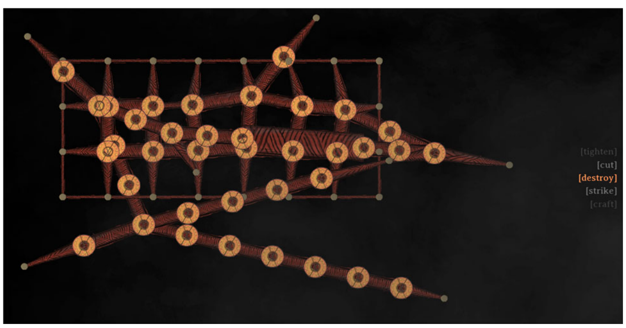

Fig. 6 Screenshot of the RURATAE environment, allowing dynamic creation/playing of 3D sounding mass-interaction models

tic signal processing) [6] provided a first means for audio rate simulation in Max/MSP, whereas SYNTH- A- MODELER [10] provides a Faust-based [58] engine allowing compilation for a variety of targets and platforms. It has since been extended with a modelling user interface and bridges allowing for interconnection between mass-interaction, waveguide and modal synthesis elements [8]. Recent developments have yielded new prototypes for 3D mass-interaction frameworks with audio and haptic capabilities [47,73] (Fig. 5), the MI-GEN toolkit for efficient simulation in Max/MSP [48], as well as RURATAE [1] a system offering a novel approach to sound-producing 3D mass-interaction models (Fig 6). Pelle Christensen's recent work drawing parallels between finite difference schemes and modular mass-interaction networks is also worth noting [22].

4.2 Force-feedback technologies

The dynamic coupling with a virtual resonating body is only as good as the haptic device that supports this coupling. In the case of virtual musical instruments, peak force-feedback, dynamic bandwidth, and the rate of the haptic closed-loop are all significant factors, each bearing technological and cost implications. Various technologies have been employed or specifically developed over the years to this end, offering different balances between performance and affordability/accessibility.

4.2.1 General purpose haptic devices

Available commercial force-feedback devices such as the *Phantom*[3] (a mid-priced stylus-based haptic device) or *NovInt Falcon*[4] (a low-cost gaming device with USB interface) are commonly used to add haptics to Digital Musical Instruments [6,67]. Such devices generally run the haptic loop at around 1kHz using asynchronous communication protocols. While this provides sufficient bandwidth to display frequencies adapted to the human tactilo-proprio-kinesthetic receptors (i.e. up to approximately 500 Hz) [43], it is largely below the frequency range of the mechanical behaviour of (real or simulated) vibrating bodies—it is therefore uncertain if the resulting coupled *human bio-mechanics/simulated instrument* system provides complete support for the closed-loop dynamics as proposed by O'Modhrain's model [59].

4.2.2 High-end synchronous haptic workstations

First studies of dynamic coupling between a user and a virtual resonating body through haptic technologies date back to the works of Florens [26] in the late 1970s, leading to the high-performance TGR (*transducteur gestuel rétroactif*) systems used in works such as [44,45,50]. Such works ensure a physical, energy-conserving *user-device-simulation* system by offering very high dynamic mechanical bandwidth (approx. 15 kHz), peak force-feedback (approx. 200 N per DoF) and by integrating the haptic position and force data streams synchronously into the closed-loop simulation at rates equal or approaching those of the acoustical physical simulation, with single-sample latency between its force input and position output. Real-time constraints for such computational loops are demanding, in terms of instrumentation, architecture and computational costs. This may be addressed using real-time operating systems and implementing multi-rate physical simulations [45]. These implementations allow for large-bandwidth dynamic coupling covering the entire acoustical range of the simulated instrument with guaranteed temporal accuracy, thus approaching the *instrumental* closed-loop system (see [50]) (Fig. 7).

4.2.3 Affordable open-hardware solutions

Partially in response to the cost and complexity of the technologies mentioned above, several open-hardware systems

[3] https://www.immersion.fr/en/phantom-touch/.

[4] From NovInt Technologies: https://hapticshouse.com/.

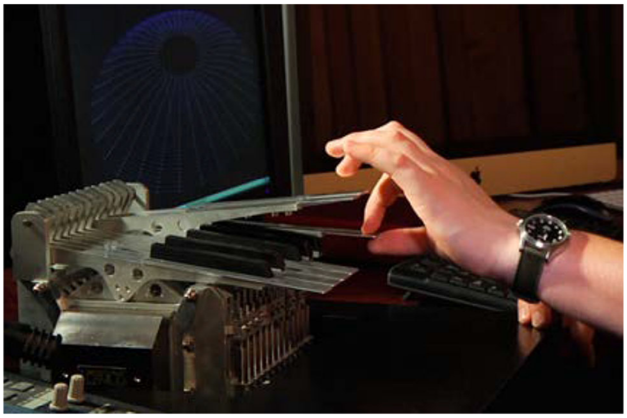

Fig. 7 The TGR device used in the *Modeleur Simulateur pour la Création Instrumentale* (MSCI) platform [45]

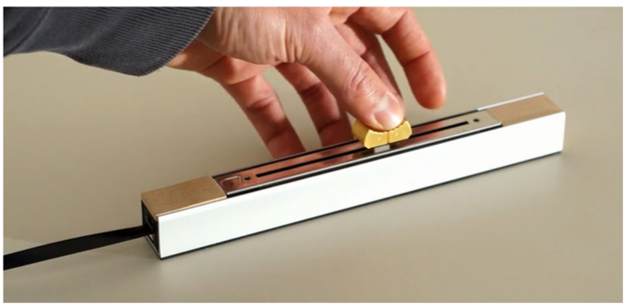

Fig. 8 The FIREFADER, a 1 DoF open-hardware haptic device based on a motorised slider and arduino micro-processor. Edition specifically built for Ableton's Loop festival by Alexandros Kontogeorgakopoulos and Odysseas Kleissouras

have been proposed, such as the simple low-tech haptic systems designed by Bill Verplank [71,72]. More recently, the rise of digital fabrication technologies and open-electronics have given birth to new, affordable and open-source and hardware haptic devices, such as Edgar Berdahl & A. Kontogeorgakopoulos' FIREFADER [5] (Fig. 8), or the HAPLY[5] system [23] (Fig. 9). These devices are cheap to build and repair, use simple communication protocols and minimise or entirely circumvent the use of any proprietary software.

While there is little question as to the limits of such solutions in instating qualitative dynamic coupling (due to low bandwidth, limits in closed-loop latency due to USB communication between computer and device, low position and force ADC/DAC resolution, cheap or 3D-printed mechanical parts, etc.), their emergence has undoubtedly pushed audio-haptic creation with physical models into a new realm, as proven by several artistic works discussed in the following section.

[5] http://www.haply.co.

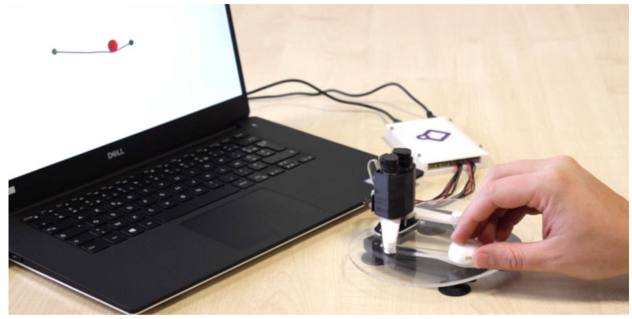

Fig. 9 Real-time audio-haptic interaction with a 2D string model designed with the MIPHYSICS engine, using a 2 DoF HAPLY force-feedback device [47]

5 Analysis of artistic works exhibiting multisensory instrumental dynamics

In this section, we propose a new angle for discussing physically-based audio-haptic DMIs by analysing a series of artistic works. Indeed, over the last ten years, the number and variety of pieces exhibiting such mechanisms has increased significantly, to the point that it can become an object of study in itself[6]—and a significant indicator of artistic interest in specific research directions. We will describe conceptual and technological frameworks pertaining to these works and try to draw certain conclusions that may provide useful information for future developments in this field.

5.1 Considered artists and works

5.1.1 Stuart rimell

The Child is Sleeping (2002) by Stuart Rimell is, to the best of our knowledge, the first documented use of real-time direct force-feedback interaction with a multisensory physical model in a musical composition. The piece involves a capella choir and a virtual physical instrument designed with Cymatic [39,63] (three "cymbal-like structures") played in real time by the composer using a combination of force-feedback joystick and mouse issued from gaming controller technologies (most likely exciting the virtual structures via percussive gestures). Unfortunately, we found little further documentation than that provided in the two papers published at the time of the creation.

5.1.2 ACROE

The theoretical positions, research advances and productions of Cadoz and colleagues are indubitably the core around

[6] Such an analysis in the scope of non-haptic use of physical models for musical composition was undertaken in 2004 by Chris Chafe—see [21].

which research into modular physical modelling and haptic interaction with simulated instruments has formed over the years. In fact, the majority of artists and researchers involved the present analysis have spent at least a short spell in Grenoble, ACROE's geographical location, at some point.

ACROE were among the first to consider such tools as being of primary importance for artistic and musical creation, calling for specific force-feedback device requirements—at a time where haptics as a domain barely existed—resulting in hardware technologies that remain unmatched to this day [28]. CORDIS- ANIMA and environments such as GENESIS have paved the way for nearly all mass-interaction software found today. The core principles of these tools have remained almost unchanged for the better part of three decades, offering a singular balance between the power of modular frameworks and a conceptual simplicity [18] that allows users with little to no technical background to take part in creative physical design and simulation.

Despite long-standing pioneering research into physical interaction with virtual instruments (see [15] for an extensive history), the afferent technologies for real time performance weren't employed in a full-scale artistic work until Claude Cadoz's *Hélios* in 2015, leveraging the ability to design large scale haptic instruments with the MSCI platform [45].

Hélios (2015)

Hélios builds upon Cadoz's compositional methodology of designing entire musical pieces as a single physical model within the GENESIS software (a technique already used in previous works *pico..TERA* and *Gaea*). It is the first work to combine both a large off-line physical scene (the backbone and structure of the piece composed of around 200000 physical elements in interaction) and live performance on a real-time instrument composed of around 7000 physical elements (using the TGR device). The instrument in question is composed of six gong-like structures that can be struck using six keys of the haptic device. A complete description of the piece is contained in Cadoz's keynote presentation at the Sound and Music Conference in 2018[7].

Quetzcoatl (2018)

Cadoz's latest work is *Quetzcoatl*, conceived in collaboration with Nicolas Castagné. It relies on very similar principles to those of *Hélios*. Little information has been publicly disclosed regarding this piece, created in 2018 at the Micro-Music festival in Romans (France), apart from the fact that it allows coupling of several users who interact jointly on the simulated model through haptic interfaces (a process equally used in A. Konterogakopoulos' *Mechanical Entanglement* and E. Berdahl's *thrOW*, discussed hereafter).

5.1.3 Lauren hayes

Running Backwards, Uphill (2011) is a composition by Lauren Hayes for violin, cello, piano and live electronics including a force-feedback device. The electronic-haptic part was developed using the HSP framework and the NovInt Falcon. Lauren used and amended some of the examples that come with the framework and designed the haptic part of the piece with the aim of evoking the same expressive qualities as the professional ensemble. In her paper presented at the International Computer Music Conference in Ljubljana in 2012, she describes some performance aspects the composition [34]:

> One of the most interesting aspects of the instrument was that depending on the different force profiles used, it could rapidly change between allowing wild gestures, to a very resistant, even secure, environment where moving through detailed nuances of a sound could be explored.

Different force profiles were used in order to enable the desired gestural behaviour. Her gestures triggered short segments of samples and affected the start and end points, the playback speed. The haptic device was also used to transduce fast gestural sweeping movements to process various effects such as bit-crushing, feedback and filtering which were applied to a second set of samples.

5.1.4 Alexandros Kontogeorgakopoulos and associates

Engraving-Hammering-Casting (2012)

Engraving–Hammering–Casting is a music composition co-created by Alexandros Kontogeorgakopoulos and Edgar Berdahl, written for two performers interacting with two force-feedback haptic devices and a series of mass-interaction physical models. The research behind the composition was presented in the form of a paper in 2012 but the piece was premiered as a solo performance in 2013 at the INTIME symposium in Coventry by Alexandros Kontogeorgakopoulos. The piece was performed again as a duo during International Computer Music Conference in Athens in 2014 [4].

This composition explores the musical applications of simulated ergotic interaction in live performance. It is inspired by the way people interact skilfully with tools and more specifically in processes such as carving, casting, cutting, drawing, forging, grinding, hammering etc. The three sections of the composition are related sonically and conceptually to the processes indicated in the title of the composition.

[7] Cadoz's keynote presentation can be found here: https://zenodo.org/record/1422493/files/smc_2018_001.pdf.

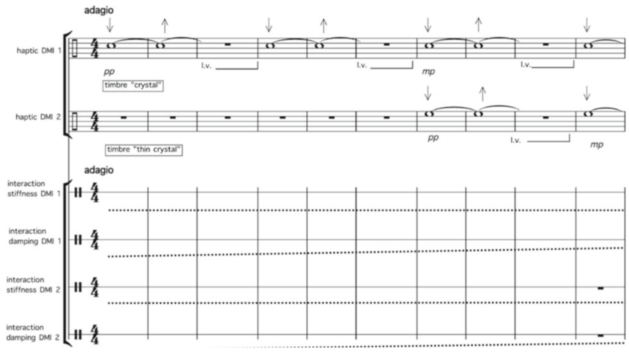

Fig. 10 *Engraving–Hammering-Casting* score section

The device employed is the NovInt Falcon. A physical model of vibrating mass-spring resonators is designed with the HSP framework and employed to generate both the sound and the haptic force feedback. The musician operates inside a square virtual shape and can interact with the sides where the reconfigurable resonators are placed. A six-stave score notates the gestural activity of the performers (which side they are exciting and how they are exciting it) and contains other Western music notation marks such as dynamics and also indicates the dynamic evolution of two interaction parameters: stiffness (k) and damping (R). Figure 10 depicts the first page of the score.

Metronom (2013)

Metronom which stands for metronome in Welsh, is a live audiovisual composition composed by Alexandros Kontogeorgakopoulos for a custom designed haptic interface designed and fabricated by himself and Olivia Kotsifa. The interface consists of four haptic faders based on the Firefader technology, and a digitally fabricated transparent acrylic structure, etched and cut according to the requirements of the music and the visual content.

The performer interacts haptically with the moving faders, which behave like metronomes, at various tempi and rhythmic motifs. The faders' mechanical sounds are recorded and processed in real-time by digital signal processing algorithms and projected sonically back into space. Moreover the positions of the faders, driven by automated procedures and altered mechanically by the performer gestures, control various compositional parameters affecting the timbre, the rhythm and the movement of various projected words and phrases. A gradual interplay between the shadows of the physical interface's structure, the human gestures and the light refraction from the acrylic surfaces shapes the visual elements of the composition. The resulting inter-media performance is an interactive audio-visual composition and a dance between the hands of the performer and the movements of the haptic interfaces (Fig. 11).

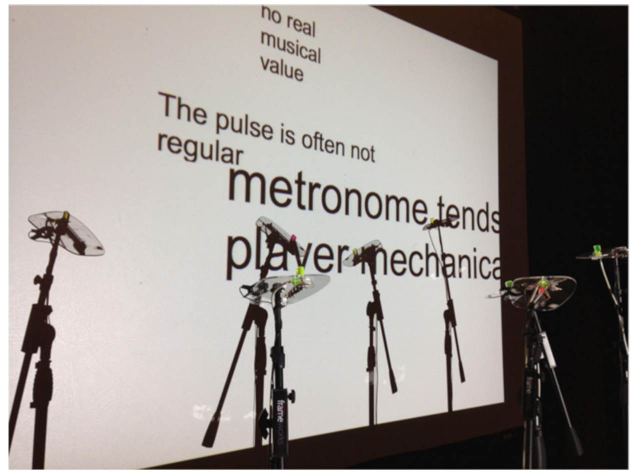

Fig. 11 *Metronom* setup as performed during the International Conference of New Interfaces for Musical Expression in 2015

Simon Emmerson imagined electronic music compositions based on the bi-directional interaction paradigm offered by haptic interfaces [24]. *Metronom* responds to this quote offering a performance where the performer is engaged with the instrument in a choreographed way that goes beyond the musical instrument paradigm.

> The world of computer-controlled "feelies" is emerging and will no doubt be integrated into musical performance. Nonetheless, the situation is at present non-symmetric: computers do not yet touch humans to any great extent. This suggests that if new two-way touch interfaces do evolve we may possibly develop relationships nearer to dance than to music as we know it to date.

In this composition, the physical model designed in HSP for the haptic processes is remarkably simple. Sequenced time-varying forces move the faders to both directions periodically at different time intervals. Therefore the faders behave essentially as metronomes, where the frequency, the amplitude of the oscillation and the time where they are active are preprogrammed. The performer can interrupt this motion with his hand, altering the final sonic result according to his gestures. The block diagram of the developed system can be seen in Fig. 12.

Mechanical Entanglement (2016)

Mechanical Entanglement is a musical composition written in 2016 for three performers and three force feedback devices by Alexandros Kontogeorgakopoulos, George Sioros and Odysseas Klissouras [42]. It is based again on the HSP framework and the FireFader haptic device. The most important and novel element of the work is that the force feedback devices are mutually coupled using a virtual mass-interaction

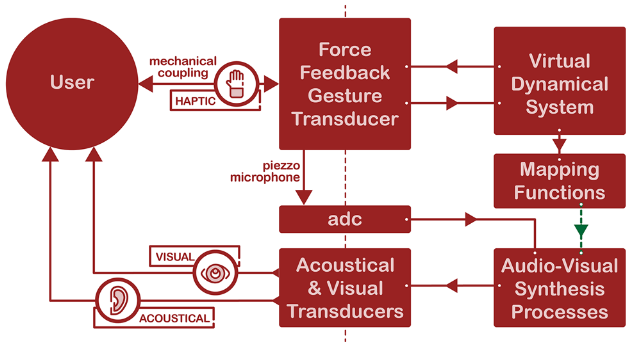

Fig. 12 *Metronom* block diagram

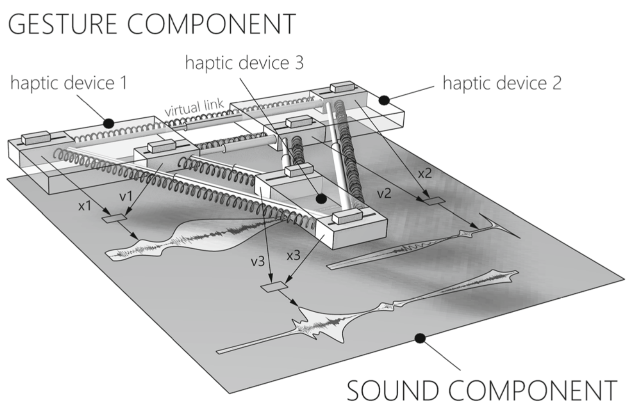

Fig. 13 3D model of the *Mechanical Entanglement* system structure

network. Therefore the performers feel each others' gestures during the performance through the haptic faders and collaboratively generate the sonic output. The system's structure is illustrated in Fig. 13.

The movement position and the speed of the faders are mapped to several signal processing algorithms that process recognisable classical and contemporary music recordings. Moreover, each section of the composition corresponds to different physical modelling parameters which affect the nature of the interaction between the performers. One of the goals of this technological and artistic research is to explore the creative possibilities of collaborative haptic musical systems where the gestures the performers are mutually influenced. It is believed that it is the first project to address this question in the Sound and Music Computing community.

The composition is based on the concept of stretching. The performers physically stretch a simulated material and at the same time they control a time-stretching algorithm. The challenge for each of them is to focus on the flow dynamics of the group's interaction environment, instead of solely mastering a deterministic musical instrument.The notion of tactile-listening is introduced in the publication describing the composition:

The performers constantly shaped and explored a "viscoelastic" environment of gestures and sound. In the physical-tactile level they were always feeling the flow of interactions between them and had to find ways of anticipating the unpredictability of their instrument behaviour. The fingertips functioned simultaneously to express the performer's own musical intention and experience the intentions of others. As such, the act of performing was indispensably connected with the act of tactile-listening, forming an enhanced tactile environment, where every performing force is applied upon forces produced by the other performers.

5.1.5 Edgar Berdahl and LSU (Louisina State University)

Edgar Berdahl's recent years as associate professor of Experimental Music and Digital Media at LSU (Baton Rouge—USA) have given rise to several musical pieces incorporating multisensory haptic interaction with physical models, by both himself and students and/or associates [9]. These works rely on tools developed or co-developed by Berdahl, namely the FireFader open-source force-feedback device, the HSP framework in the Max programming environment and the SYNTH- A- MODELER software. Most of the descriptions below come from the publication mentioned above and from Edgar's website[8].

Transmogrified Strings (2014)

Transmogrified Strings is a piece by Edgar Berdahl, presented for the first time at the International Computer Music Conference in 2014. It features an eight-channel FireFader design (shown in Fig. 14), allowing one to pluck eight virtual strings (modelled with mass-spring networks) whose physical parameters are modulated at audio-rate, constituting somewhat of a "physical" counterpart to classic frequency modulation synthesis techniques [3]. Moreover, in one section of the composition a string is made to fall apart into individual, disconnected masses. The designed string model uses conditional links instead of linear springs, resulting in percussive granular sounds. This model was widely used at ACROE offline simulations with the GENESIS environment to model maracas and to synthesise rattle sounds. However within this environment, the user doesn't have the possibility to dynamically alter the parameters of the networks such as the threshold of the conditional link in Edgar's model. The composition is an interesting example where the physical modelling formalism is used in a innovative way to create models that cannot appear in real life. Nonetheless, the nature of the interaction keeps its physical nature and the hybrid strings retain their tangible characteristics.

8 http://edgarberdahl.com/tag/music/.

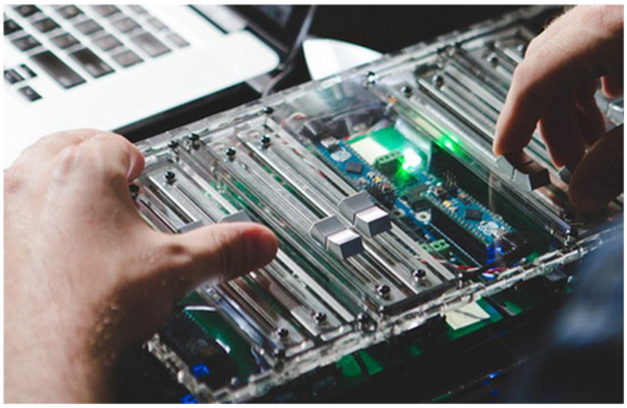

Fig. 14 The 8 x 1-Dof FireFader system built by Berdahl for his piece *Transmogrified Strings*

thrOW (2014)

thrOW is a composition written by Edgar Berdahl for the Laptop Orchestra of Louisiana, premiered in 2014. It appears to be the first piece of music written in which multiple performers can interact haptically with the same virtual objects. Each performer in the orchestra uses two force-feedback faders to interact with a mass-interaction physical model which in turn controls the amplitude of synthesised sine waves.

The compelling aspect of the composition is that the performers, as they move the faders, can throw the virtual masses back and forth between each other. This creates an engaging collaborative experience which shapes the produced musical outcome. When those masses bounce against the haptic fader's knob, a sound output is generated, which is different for each performer. Gravity is added to the model and altered abruptly during the composition, affecting the motion of the moving masses.

Quartet for Strings (2016)

Quartet For Strings is a composition by Stephen David Beck for four haptic devices. It is a quartet for four virtual non linear strings modelled with the mass-interaction physical modelling paradigm [7] (Fig. 15). It was performed by the Laptop Orchestra of Louisiana in 2016 at the International Conference on New Interfaces for Musical Expression (NIME) in Australia.

Two special performance techniques are exploited in this piece, afforded by the design of the instrument. Those techniques are described in [9]. The composition is fully scored, with three-line staves representing relative pitch elements and various expressive markings. Figure 16 presents a small segment of the score.

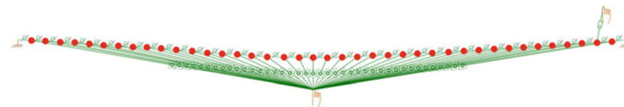

Fig. 15 Representation of a slack string used in Stephen David Beck's *Quartet for Strings* (image taken from [9])

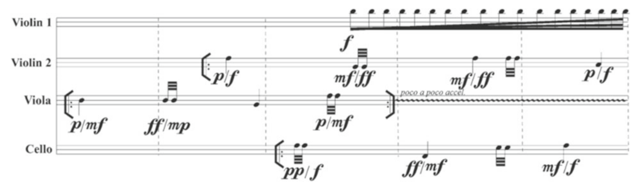

Fig. 16 Small excerpt from *Quartet for Strings*

Of Grating Impermanence (2016)

Of Grating Impermanence is a composition by Andrew Pfalz for two "Haptic Capstans" [65] (devices with motorised rotary potentiometers, based on the FireFader design), performed for the first time at NIME 2016. It illustrates real-time sound production strategies coupling both force-feedback controls and common controllers, such as the computer keyboard. The piece experiments on abstracting and easing control over certain parameters of the sound or music production, in a way that performers can still handle them while increasing their focus on gesture and mechanical relation to the instruments (Fig. 17).

The composition is written for two virtual harps developed by Eric Sheffield using the Synth-a-Modeler environment. Each harp is composed of twenty digital waveguide strings, plucked with the haptic fader. The physical parameters of the strings are altered in real-time from another fader without force-feed back while their tunings are pre-programmed as presets and selected via the laptop keyboard. A distortion effect further alters the sonic output, controlled likewise by the arrow keys of the computer keyboard.

The sections of the composition demonstrate various performance techniques, scored accordingly. In the beginning and ending sections, certain musical aspects such as the precise rhythm are left open to the interpreter's choice, whereas other elements such as the timing for chord-tuning changes, performed notes or timbre alteration (controlled by the second fader) are notated precisely. The interior sections are fully notated. It is interesting to notice that the performers follow the score with the keyboard without having the freedom to select notes individually.

Guest Dimensions (2016)

Guest Dimensions is a quartet piece composed by Michael Blandino for four haptic faders, premiered at NIME 2016. The physical models employed in this composition are two

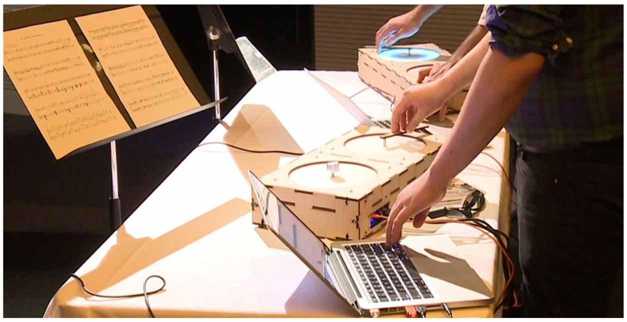

Fig. 17 Two Haptic Capstans (1-Dof rotary haptic devices) used in Andrew Pfalz's *Of Grating Impermanence*

virtual resonators with modal frequencies obtained from the sound of granite blocks and from the gayageum (a Korean musical instrument). The piece is performed from a fixed score. Yet, the selection of all notes is automated. During the performance, each performer plucks one of the two virtual resonators. The different sections of the composition correspond to a different set of parameters: fundamental frequency, decay times, reference mass values, pluck interaction stiffness, pluck interaction damping parameter, and virtual excitation location. A simple visual feedback enables more precise gestures from the performers and helps them in locating the points of contact with the physical models.

Two plucking performance techniques are notable in this piece: the tremolo and the legato. Those techniques were facilitated by the programmable nature of the force feedback. The stiffness of the virtual plectrum decreased for the legato and increased for the tremolo accordingly.

This feature is one of the most interesting ones with Digital Musical Instruments with programmable haptic feedback, a fact that was emphasised in several works presented above. For example Hayes selected different force profiles to change her gestural behaviour during the piece and Kontogeorgakopoulos used different coupling parameters between the performers to affect the nature of the interaction.

5.2 Elements of analysis

Although they are all quite different in terms both of nature and deployed technology, the above works can form a basis for some preliminary remarks regarding use-cases, aesthetic interests and design trends for haptic digital musical creations relying on instrumental dynamics. While a formal and in-depth analysis of the singularities and invariants among these works is beyond the scope of this paper and would require additional methodological tools, we offer some preliminary insight and remarks.

5.2.1 Mass-interaction physics as a common ground

All of the works presented above employ mass-interaction physical modelling as a common means to craft virtual objects and design ways to interact with them (with extensions to waveguide and modal synthesis in the case of SYNTH- A- MODELER). We believe that the following criteria may explain the predominance of mass-interaction (MI) physics in such works:

1. **Multiple Physical Layers**: MI allows for seamless design of purely mechanical objects, aero-acoustical vibrating objects, and haptic interaction within a unified physical framework.
2. **Scalability**: MI models are scaleable from extremely elementary mechanical constructs to vast physical ecosystems and are built using a relatively simple and intuitive modular construction system that requires little prior knowledge of physics, musical acoustics, or computing.
3. **Creative Tools**: to this day, MI frameworks are the only ones to offer fully modular tools for artistic creation, either in proprietary systems (such as GENESIS) or in toolkits for general creation environments (such as Max/MSP). These tools allow for *ground-up* model design, and not just parametrisation and interconnection of existing macro-structures (cf. works such as [11,40]).
4. **Moderate Computational Cost**: MI models offer efficient computation, while allowing for arbitrary physical topologies and extensive real time control (topological changes, parameter modification, etc.), encouraging creative approaches to physically-based sound synthesis. While the choice of full modularity does circumvent possible omptimisations (e.g. for specific physical topologies), the resulting creative freedom separates it from most other physical modelling frameworks.

It goes without saying that the above criteria are topical issues in current works (see Sect. 4.1.3) and much yet remains to be accomplished, as will be mentioned in Sect. 6.

5.2.2 The bidirectional gesture-sound Chain

While all the works related in Table 1 provide direct haptic coupling with physical models for audio-haptic creation, not all of them implement a complete gesture-to-sound chain. In fact, *thrOW*, *metronom*, *Mechanical Entanglement* and *Running Backwards, Uphill* do not produce sound by means of the physical model itself, instead using classic synthesis or transformation processes. One might be tempted to classify them as classic haptic-augmented DMIs. However, they each feature coupled dynamics between one (or several) human bodies and virtual physical entities as a central component

Table 1 Corpus of audio-haptic pieces including haptic interaction with physical models

Piece	Author	Haptic technology	Software technology	Instrumentation/Principles
The Child is Sleeping (2002)	Stuart Rimell	Gaming Force Feedback Devices (Joystick & Mouse)	Cymatic	Capella choir & simulated physical instrument (three cymbal-like structures controlled in real time)
Running Backwards, Uphill (2011)	Lauren Hayes	NovInt Falcon	Haptic Signal Processing (HSP)	Piece for violin, cello, piano and live electronics including a haptic device and simple physical models with different force profiles
Engraving- Hammering- Casting (2012)	Alexandros Kontogeorgakopoulos and Edgar Berdahl	NovInt Falcons	Haptic Signal Processing (HSP)	Haptic interaction with virtual resonators with changing physical properties throughout the piece
Metronom (2013)	Alexandros Kontogeorgakopoulos	FireFaders	Haptic Signal Processing (HSP)	Several haptic devices behaving as metronomes (with simple physical models), affecting sound and visual elements. Real-time processing of the mechanical sounds of the haptic interfaces
Transmogrified Strings (2014)	Edgar Berdahl	FireFaders	Synth-A-Modeler	Using a custom designed casing holding 8 FireFaders, the performer plucks virtual strings, while their physical parameters are modified in real time
thrOW (2014)	Edgar Berdahl	FireFaders	Synth-A-Modeler	Virtual masses are thrown and caught between several performers, triggering musical events. Performed by Laptop Orchestra of Louisiana
Hélios (2015)	Claude Cadoz	Tranduscteur Gestuel Rétroactif (TGR)	GENESIS & MSCI	Piece entirely composed of a large off-line physical model (200000 modules) and a real-time model (7000 modules)
Quartet for Strings (2016)	Stephen David Beck	FireFaders	Synth-A-Modeler	Quartet of FireFaders, plucking four virtual strings
Of Grating Impermanence (2016)	Andrew Pfalz	Haptic Capstans (FireFader variation)	Synth-A-Modeler	Quartet of FireFaders, strumming four virtual harps (20 strings each)

Table 1 continued

Piece	Author	Haptic technology	Software technology	Instrumentation/Principles
Guest Dimensions (2016)	Michael Blandino	FireFaders	Synth-A-Modeler	Quartet of FireFaders plucking physical resonators, configured to match timbre of prerecorded percussion samples
Mechanical Entanglement (2016)	Alexandros Kontogeorgakopoulos, George Siorros and Odysseas Klissouras	FireFaders	Haptic Signal Processing (HSP)	Three performers are haptically connected through a physical model. Stretching drives audio transformations
Quetzcoatl (2018)	Claude Cadoz, Nicolas Castagné	Tranducteur Gestuel Rétroactif (TGR)	GENESIS & MSCI	Large off-line physical model and real-time virtual instrument jointly interacted with by two performers

The physical modelling techniques for each of these works rely on the mass-interaction paradigm (recent SYNTH- A- MODELER works such as *Of Grating Impermanence* or *Guest Dimensions* also include hybrid mass-interaction/waveguide models/modal synthesis)

of the artistic process, which certainly warrants their place in our proposed corpus.

Furthermore, the complete gesture-sound chain may be questioned in other above works that *do* rely on physical sound synthesis, in particular those that employ ballistic percussive interaction with the virtual model. Indeed, if—in the case of the acoustic piano—one disregards overall vibration of the piano soundboard that may propagate into the keys, the instrument's double escapement mechanism provides a natural decoupling from gesture to sound, forming two separate phases: *player/hammer* coupling and *hammer/string* coupling phases are mutually exclusive. As an example, while the technological components used *Hélios* allow for complete gesture-sound coupling [27], the instrument's mechanical design uses a hammer percussion with an escapement mechanism, thus creating a discontinuity in the chain. Pushing this reflection, one might consider a heavy-touch electrical piano controller to be a perfectly suitable, and much cheaper, input device.[9]

Our objective is by no means to impose a diktat of what are true *viable* audio-haptic coupling contexts. Nonetheless, reflections of this nature may be of help in specifying interaction features and assessing the benefits of employing haptic technologies in Digital Musical Instrument design.

5.2.3 Interpersonal connection through virtual physical objects

Three of the above works (*Mechanical Entanglement*, *Quetzcoatl*, *thrOW*) use force-feedback interfaces and shared simulated physical objects as a means to provide direct haptic connection between the performers. Technologies such as the FireFader provide simple means for communication between the simulation and several haptic devices, as each peripheral communicates via serial protocol over USB connection.

As an increasing number of studies take interest in the role of haptics in emotion perception [64] including during virtually mediated interpersonal contact [2,68], this perspective appears particularly promising in establishing a strong bond between performers and allowing for collective musical co-construction.

6 Prospective and discussion

6.1 New views—new instruments—new art

After spending many years as a somewhat secondary concern in the acoustics, interaction and computer music communi-

[9] One could wonder whether simple vibrotactile audio feedback in the keys of an electric piano interface (see [29]) would yield a greater sense of presence and realism than a full haptic piano mechanism simulation.

ties, the physicality of the performer-instrument interaction is now becoming an object of central attention, driven by impulses that shed new light on the intertwined roles of the brain, the sensorimotor system, and the coupled dynamics of human bio-mechanics and instrumental mechanisms. Haptics constitute a unique means to explore this area, by analysing embodied cognition processes [31], quantifying the impact of energetic exchange between body and instrument [50], and more generally yielding interwoven scientific and artistic challenges and breakthroughs.

Progressively, these practices are starting to make their way into digital musical instrument design, and if the artistic works mentioned above are anything to go by, they could very well represent the emergence of a new branch of DMIs that opt for *"motor intent and impedance rather than control authority"* (to quote O'Modhrain and Gillespie once again), focusing on the importance of dynamic physical coupling for discovering, learning and perfecting instrumented tasks.

It is encouraging that big companies in the music technology industry are starting to express an interest in haptics. A good example is the initiative from Ableton to organise a panel entitled *A Sense of Touch: Haptics in New Musical Instruments* during their *Loop* festival in 2017, in which Alexandros Kontogeorgakopoulos and Lauren Hayes were invited to discuss the role of haptics in music making[10].

Conversely, for the first time it is now possible to analyse audio-haptics through artistic creations: people are no longer just *foreseeing the potential* of force-feedback for music or art, they are actually *doing it*. This, in our view, is a huge step forward and one that could provide a significant drive for the scientific community.

6.2 Remaining technological challenges

None of this would exist, if it were not for continuous advances and large-scale democratisation of technological components, especially during the last twenty years. While these developments open vast new areas of exploration, many challenges still lay ahead, some of which are discussed below.

Physical Modelling Frameworks. While commercial real-time physical sound synthesis applications have made their way into mainstream music technology, open toolkits and environments have dramatically increased accessibility and sparked strong interest among artistic and music-tech communities, allowing them to finally take instrument design into their own hands. A possible challenge ahead may be to unite this multitude of similar, yet disparate, open-source tools, encouraging common standards allowing to transfer concepts, models, or even haptic virtual instruments across systems or devices. Another current challenge lies in harnessing the potential of non-linear three-dimensional mass-interaction models for sound synthesis, as related in [73].

Haptic Technologies. Research on the topic of force-feedback technologies continues to advance, offering both new technological solutions and further understanding of human haptic action and perception. However, to this day, working with haptic devices still imposes a radical choice of performance over accessibility, or vice-versa:

- High-performance metrological force-feedback devices such as the TGR are expensive expert laboratory tools, confined to academia. However, they are currently the only solutions to provide sufficient performance to allow fine characterisation of dynamically coupled body/instrument systems, and as such are invaluable tools in experimental validation.
- Flexible open-source force-feedback devices are affordable enough to be owned and used by artists, however they do suffer from severe limitations (mechanical parts, dynamic bandwidth, number of DoF, closed-loop latency, etc.). Today, we could be tempted to say that they are devices for *thinking and designing* dynamic coupling with virtual musical instruments, but they do not yet entirely allow qualitative *feeling* of this coupling.

The majority of artistic works covered in this paper (with the notable exception of those conducted at ACROE) tend to favour affordable and relatively low-performance devices, either by choice or by lack of access to costlier equipment. Time and more importantly interest from the Musical Haptics community should help mitigate the limitations of such devices, and we can hope to see technologies that allow for superior dynamic coupling qualities while remaining affordable in the coming years. In fact, projects such as Wooden Haptics[11] already provide interesting middle-grounds between accessibility and performance (although to our knowledge, this particular device has not yet been used in the context of musical research/creation).

6.3 Towards multisensory artistic forms

When analysing the works mentioned in the previous section in the light of the theoretical positions discussed in the opening sections of this paper, it appears that although most, if not all, of this research and creation originates from a musical context, its scope and core concerns go beyond. The central artistic object is not only how the tight gesture-sound link may produce expressive sonic content, but rather on

[10] https://loop.ableton.com/2017/.

[11] https://woodenhaptics.org/.

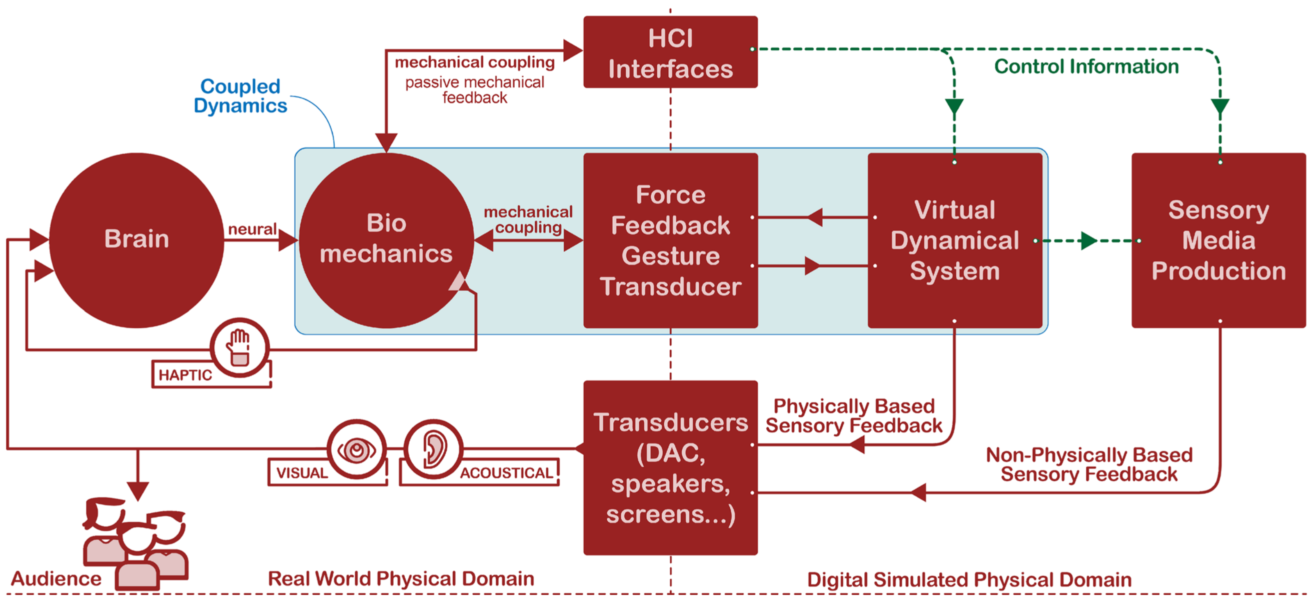

Fig. 18 A generalised representation for multisensory instrumental dynamics chains such as those in the artistic works presented in Sect. 5

the emergent multisensory properties of dynamically coupled systems: for instance, how coupling can organically alter the physical behaviour of an object, how humans may feel each other through shared coupled dynamics, how humans can adapt during coupling with virtual objects whose dynamical properties change over time, how emergent coupled physical dynamics can inspire improvisation...

Consequently, perhaps a more adequate denomination for these practices would be: works that explore *multisensory instrumental dynamics*, with the artistic outcome being a possible combination of any sensory media (sound, visual motion, haptic experience felt by one or several individuals) resulting from the emergent coupled system. A possible block diagram decomposition applicable to the presented works is shown in Fig. 18.

– Sensory feedback (encompassing auditory and visual feedback) may be physically-based (i.e. produced by the virtual dynamical system) or generated through other means (through a sensory media production unit).
– The dynamically coupled performer/instrument system is represented in blue. It could extend to multiple performers, each player's bio-mechanics then contributing to the overall dynamically coupled system.
– Green lines represent complementary information-based control, possibly mediated through mapping strategies. Traditional HCI (that may provide passive haptic feedback to the user) can allow modification of the virtual physical system's properties or driving the sensory media production outside of the dynamic haptics loop. The virtual physical system itself may drive production of sensory media.

In order to maintain readability, special cases such as Brain Computer Interfaces and free-air control (providing no passive feedback) have not been represented, nor has the possibility of external agents sending control information to the virtual dynamical system or sensory media production unit (e.g. parameter control by other processes or individuals, planned automation changes, etc.). Haptic feedback directed towards the audience is also omitted, although it has been the subject of recent works such as [70].

7 Conclusions

Through this work, we have presented and discussed topical research questioning the nature of the interaction between performer and instrument through the notion of *multisensory instrumental dynamics*. We have then elaborated on how this research may transpose into the realm of digital musical instruments by employing unitary, or multisensory, physical models coupled with force-feedback devices. Numerous technological challenges still lay ahead to fully address this issue. Nevertheless, we believe that, at their core, digital instruments designed this way may exhibit comparable manipulation, assimilation and embodiment processes to those of acoustical instruments. We also hope that such perspectives will contribute to spark a broader interest in the potential of multisensory instrumental dynamics in the wider scope of human–computer interaction, beyond music and artistic creation.

Several artistic works have employed this approach to physical interaction with virtual musical instruments, from as early as 2002, and with considerable acceleration in recent years thanks, in part, to the increasing accessibility of open-source and open-hardware physical modelling and force-feedback technologies. We believe such works are of strong significance for the Musical Haptics and Haptics communities, who have long been interested in applications of force-feedback in the scope of artistic creation, and can now explore a new terrain for practice-based studies, for designing new technologies with the user-in-the-loop, and more generally for a fruitful confrontation between artistic practices and scientific research.

This may represent a first turning point towards multisensory art forms focused on the physical dynamics between (possibly multiple) player(s) and simulated physical entities. The tendency in recent works to exhibit shared physical experiences through force-feedback interaction is particularly enticing in regards to research linking haptic experience to human emotion and interpersonal communication.

Finally, in a time where the tech industry is rapidly shifting the focus of haptics as we know it towards vibrotactile touch-screen interfaces and *mid-air haptics* for mixed realities, the musical and more generally the artistic question still calls for qualitative, tangible interaction with virtual objects, mediated through true force-feedback technologies. Without moving too far out of our comfort zone, we could posit that the "magic" that we, as humans, experience when interacting with an instrument (be it musical or otherwise) is in no small amount linked to the discovery and progressive mental and physical incorporation of the new dynamical system composed of ourselves and the instrument. If technology allows this kind of magic to occur when interacting with a virtual instrument, or when interacting with each other through a virtual instrument—then this path is unquestionably one worth exploring, both for artistic purposes and for the development of human computer interaction.

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