Large-scale real-time Modular Physical Modeling Sound Synthesis

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ABSTRACT

Due to recent increases in computational power, physical modeling synthesis is now possible in real time even for relatively complex models. We present here a modular physical modeling instrument design, intended as a construction framework for string- and bar-based instruments, alongside a mechanical network allowing for arbitrary nonlinear interconnection. When multiple nonlinearities are present in a feedback setting, there are two major concerns. One is ensuring numerical stability, which can be approached using an energy-based framework. The other is coping with the computational cost associated with nonlinear solvers—standard iterative methods, such as Newton-Raphson, quickly become a computational bottleneck. Here, such iterative methods are sidestepped using an alternative energy conserving method, allowing for great reduction in computational expense or, alternatively, to real-time performance for very large-scale nonlinear physical modeling synthesis. Simulation and benchmarking results are presented.

1. INTRODUCTION

One goal of physical modeling synthesis is the emulation of existing musical instruments, perhaps with extensions in terms of design and functionality not easily realisable in the real world. Another is the design of new instruments, without a real-world reference. The hope is that through adherence to the laws of physics, synthetic sound of a natural acoustic character can be produced. In this setting, modularity is an important concept—the idea is to give the user control over instrument design through the interconnection of semi-independent modules. In this contribution, a modular network, consisting of a set of string- or bar-like elements coupled through an auxiliary nonlinear connection network is presented.

Modularity in physical modeling synthesis is not new. The earliest attempt at a complete synthesis system, due to Cadot [1], had such a modularity principle explicitly built in—the basic elements were masses and springs, through the interconnection of which more elaborate instruments could be constructed. The MOSAIC (later Modalys) system [2] uses the same notion, now employing modal synthesis [3]. Modular networks have also been proposed using wave-based methods [4] and time-stepping schemes—see, e.g., [5, 6]. The main difficulty is in simulating a network connected in a feedback configuration—a problem compounded when nonlinearities, essential for any musically-interesting sound output, are present. The complications are similar to those which occur in virtual analog modeling, but now in a mechanical setting, where individual elements have a distributed character.

Two main technical concerns emerge: one is ensuring numerical stability, as numerical methods for nonlinear systems are prone to explosive unstable solution growth. Another is computational efficiency: iterative methods (such as, e.g., Newton-Raphson [7]) commonly used in nonlinear ODE/PDE solvers, can lead to large increases in computational cost. For the problem of numerical stability, energy techniques are probably the only known method. Such methods, in different guises, have been popular in virtual analog applications (port-Hamiltonian approaches [8], wave digital filtering [9][10], and used in PDE solvers [11]). For general nonlinearities, however, including those involving collision or intermittent contact, energy methods are available, but usually require the use of iterative methods. See, e.g., [12][13][14].

Recently, a new class of methods has been proposed in the context of virtual analog modeling, relying on energy quadratisation [15], leading to numerical methods which are resolvable without recourse to iterative methods, and which maintain the notion of an energy balance leading to a numerical stability guarantee—see [16][17], as well as [18] in the context of audio systems. Such an approach reduces computational costs by as much as an order of magnitude, and allows for the simulation of relatively complex nonlinear systems in real time on standard hardware.

In Section 2, a modular physical modeling synthesis system is presented, consisting of an interconnection of string- or bar-like primitives, and with nonlinear connections which allow intermittent contact. A numerical discretisation scheme is presented in Section 3 allowing for energy-stable non-iterative simulation. Simulation results, illustrating characteristic behaviour of such a modular synthesis system appear in Section 4. Performance results for a C implementation are presented in Section 5 demonstrating the possibility of real-time operation of relatively complex instrument designs. Some perspectives appear in Section 6.

2. A MODULAR INSTRUMENT MODEL

The canonical building block here is the linear bar or string (referred to henceforth here as a stiff string), of circular cross section, assumed to vibrate transversely in a single polarisation. The basic equation of motion (see, e.g., [11], as well as other closely-related forms [19][20]), under enforced conditions, is of the form

\[
Lu = 0
\]  

(1)

where the linear partial differential operator \(\mathcal{L}\) is defined as

\[
\mathcal{L} = \rho A \frac{\partial^2 u}{\partial t^2} - T \frac{\partial^2 u}{\partial x^2} + E I \frac{\partial^4 u}{\partial x^4} + 2\rho A \sigma_0 \frac{\partial u}{\partial x} - 2\rho A \sigma_1 \frac{\partial^2 u}{\partial x^2}
\]  

(2)

Here, \(u(x,t)\) is the transverse displacement of the stiff string, in m, as a function of time \(t \geq 0\), in s, and spatial coordinate \(x \in \mathbb{R}\).
The equation (1) requires two initial conditions: ∂u/∂t = 0 under unforced conditions. This will be maintained here in order to examine energetic behaviour. For system (1), an excitation may be added as d

\[ (\rho E r T \sigma_0 \sigma_1 L) \]

where here, d denotes a spatial Dirac delta function selecting the excitation location x_e ∈ [0, L]. The pointwise character of the excitation can be easily extended to the case of distributed contact (as in, e.g., the case of a piano hammer or bow). Simple choices of the excitation function, if intended to model a strike or pluck, are raised cosine distributions of the form

\[ f_e(t) = \frac{1}{2} f_{e,\text{max}} \left( 1 - \cos \left( \frac{q(t-t_e)}{t_c} \right) \right), \quad t_e \leq t \leq t_e + T_e, \quad \text{otherwise} \]

where t_e is the starting time of the excitation, T_e is the duration, f_{e,\text{max}} is the maximum force, in N, and where q = 1 for a pluck and q = 2 for a strike. See Figure 1.

From an energetic standpoint, one may again multiply (9) by ∂u/∂t, and then integrate over D to obtain the energy balance:

\[ \frac{d}{dt} H_s + Q_s = \oint \int_D \rho A \sigma \partial_x^2 u \ dx \]  

where \( H_s \) and \( Q_s \) are as in (8), and where \( P \) is the instantaneous input power due to the excitation. Thus the rate of growth of energy in the system may be bounded in terms of supplied power.

2.2. Connection to a Lumped Object

Consider now a coupled system of a string under excitation, and in pointwise contact, at location \( x = x_c \), with a lumped object of mass \( M \) which is constrained to travel parallel to the plane of polarisation of the string, and with displacement \( w = w(t) \):

\[ \mathcal{L} u = -\delta(x-x_c) f_e + \delta(x-x_c) f_e \quad \frac{d^2 w}{dt^2} = f_e \]

where \( f_e \) is the connection force, assumed dependent on

\[ \eta = u(x_c, t) - w(t) \]

the relative displacement between the lumped object and the string at the connection point. See Figure 2.

Many choices for the interaction force \( f_e \) are possible. A basic linear/cubic restoring force served as a basis for the modular network presented in [5]. A more general choice, allowing for intermittent loss of contact (or collisions), and considerably widening
the range of possible sound output, is the following choice:

\[ f_c (\eta) = K [\eta - \epsilon_+^\alpha \text{sgn} \, (\eta)] \]  

(14)

Such a force law is parameterised by \( K \geq 0 \), a stiffness constant, \( \alpha \geq 1 \), a nonlinearity exponent inspired by models in contact dynamics \([23, 19]\), and \( \epsilon \geq 0 \), an effective length of the lumped object, which is now able to rattle, and which allows for a dead zone where no force is exerted by the lumped object on the string and vice versa. The notation \([\cdot]_+\) indicates the “positive part of.” See Figure 3. Note that when \( \epsilon = 0 \), so that the lumped mass and string are always in contact, the force (14) reduces to a linear connection when \( \alpha = 1 \), and a cubic nonlinear force when \( \alpha = 3 \). It is also possible to go further here, and introduce a model of contact loss, as per similar models in contact dynamics (see, e.g., \([23]\)), and employed in musical instrument modeling \([13]\).

At this point, we introduce the potential \( \phi \), such that

\[ \phi (\eta) \geq 0 \quad f_c = d\phi / d\eta \]  

(15)

and note that, through the chain rule,

\[ d\phi / d\eta = f_c d\eta / dt \]  

(16)

Given the non-negativity of \( \phi \), it is also possible to define \( \psi \) as

\[ \psi = \sqrt{2\phi} \quad f_c = \psi d\psi / d\eta \]  

(17)

This quadratisation of the potential energy has been employed in the context of virtual analog modeling and musical acoustics in \([17, 24]\) and also, recently, in much more general numerical settings, where it is referred to as invariant energy quadratisation—see, e.g., \([15]\). In the case of the force characteristic given in (14), the corresponding forms of \( \phi \) and \( \psi \) are

\[ \phi (\eta) = \frac{K}{\alpha + 1} [\eta - \epsilon_+^{\alpha + 1}] \quad \psi (\eta) = \sqrt{\frac{2K}{\alpha + 1} [\eta - \epsilon_+^{\alpha + 1}]} \]  

(18)

Though the forms in (15) and (17) are equivalent, in the numerical context, they lead to distinct energy-conserving methods—in particular, the form in (15) leads to a form requiring iterative solution, and that in (17) to one which may be resolved explicitly. For a direct comparison of this distinction in a simplified case, see the companion paper \([18]\).

From an energetic standpoint, multiplying the first of (12) by \( \partial_t u \) and integrating over \( D \) yields

\[ dH_s / dt + Q_s = P - f_c \partial_t u (x_s) \]  

(19)

Multiplying the second by \( dw / dt \) gives

\[ \frac{d}{dt} \left( \frac{M}{2} \left( \frac{dw}{dt} \right)^2 \right) = dw / dt f_c \]  

(20)

Adding (19) and (20) gives, then

\[ \frac{d}{dt} H_s + Q_s + \frac{d}{dt} \left( \frac{M}{2} \left( \frac{dw}{dt} \right)^2 \right) + f_c (\partial_t u (x_s) - dw / dt) = P \]  

(21)

But, using

\[ dw / dt = \partial_t u (x_s) - dw / dt \]  

as well as (16) leads to the energy balance

\[ dH / dt + Q_s = P \]  

(23)

where

\[ H = H_s + H_c \geq 0 \quad H_c = \frac{M}{2} \left( \frac{dw}{dt} \right)^2 + \phi \geq 0 \]  

(24)

Thus the total energy \( H \) of the system may be decomposed into the energy of the stiff string \( H_s \) and that of the connection mechanism \( H_c \), and as before is non-negative—its rate of growth may again be bounded in terms of the input power \( P \). Such a connection mechanism is passive (and furthermore lossless).

2.3. A Complete Modular Network

The step to constructing an arbitrary network is relatively straightforward, using the model above as a starting point.

Suppose a network is defined with \( N_c \) stiff string elements, each characterised by a parameter set \( \{q^{(q)}, q = 1, \ldots, N_c\} \), of the form given in (3). For each element, the associated transverse displacement is \( x^{(q)} = x^{(q)} (x, t) \), for \( x \in D^{(q)} = [0, L^{(q)}] \), and the associated partial differential operator is \( \mathcal{L}^{(q)} \). Suppose also that there are \( N_m \) lumped objects, of mass \( M^{(j)} \) kg, and of displacement \( w^{(j)} (t), j = 1, \ldots, N_m \). See Figure 4.

![Figure 4: Modular network of stiff strings and lumped masses, with connections indicated as yellow lines.](image-url)
The force \( f^{(v)}(x^{(v)}) \) is assumed to be related to an underlying potential energy \( \phi^{(v)}(x^{(v)}) \geq 0 \) as

\[
f^{(v)}_c = dp^{(v)}/dt^{(v)}
\]

(26)

In this case, \( \phi^{(v)} \) will be chosen to be of the form \( [13] \), but any non-negative form is possible. Furthermore, define the index sets

\[
I^{(q)} = \{ \nu \in \{1, \ldots, N_c \} \mid q_\nu = q \} \quad (27a)
\]

\[
I^{(f)} = \{ \nu \in \{1, \ldots, N_c \} \mid f_\nu = j \} \quad (27b)
\]

Finally, assume \( N_c \) excitation functions \( f^{(v)}_c \), \( \xi = 1, \ldots, N_c \), acting on the stiff strings with index \( q_\xi \) where \( q_\xi \in \{1, \ldots, N_c \} \) at locations \( x^{(v)}_c \). Define also the index set

\[
I^{(q)} = \{ \xi \in \{1, \ldots, N_c \} \mid q_\xi = q \}
\]

(28)

The excitation functions \( f^{(v)}_c \) could be chosen as in \([10]\).

The complete system is:

\[
\frac{d}{dt} H_s + Q_s = \sum_{\nu \in I^{(q)}} f^{(v)}_c \partial_{t} u^{(v)}_c \left( x^{(v)}_c \right) = P^{(q)}
\]

(30)

where \( H_s \) and \( Q_s \) are stored energy and power loss for stiff string \( q_\nu \), as defined in \([2]\), with parameter set \( \gamma^{(q)} \) and where \( P^{(q)} \) is of the form given in \([21]\). Summing over all strings gives

\[
\frac{d}{dt} H_s + Q_s + \sum_{\nu = 1}^{N_c} \sum_{\nu \in I^{(q)}} f^{(v)}_c \partial_{t} u^{(v)}_c \left( x^{(v)}_c \right) = P
\]

(31)

where

\[
H_s = \sum_{\nu = 1}^{N_c} H^{(q)}_\nu \quad Q_s = \sum_{\nu = 1}^{N_c} Q^{(q)}_\nu \quad P = \sum_{\nu = 1}^{N_c} P^{(q)}
\]

(32)

are the total stored energy, dissipated power and supplied power for the set of stiff strings. Recognising that the sets \( I^{(q)} \) form a partition of the set \( \{1, \ldots, N_c\} \), one has, simply,

\[
\frac{d}{dt} H_s + Q_s + \sum_{\nu = 1}^{N_c} f^{(v)}_c \partial_{t} u^{(v)}_c \left( x^{(v)}_c \right) = P
\]

(33)

Similarly, multiplying \([29b]\) by \( dw^{(j)}/dt \), and summing over \( j \in \{1, \ldots, N_m\} \), again using the partitioning property of \( I^{(j)} \), gives

\[
\frac{d}{dt} \sum_{j = 1}^{N_m} \left( M^{(j)} \frac{dw^{(j)}}{dt} \right)^2 - \sum_{\nu = 1}^{N_c} f^{(v)}_c \frac{d}{dt} w^{(v)} = 0
\]

(34)

Adding \([33] \) and \([34] \) gives, using \([25] \) and \([26] \),

\[
\frac{dH}{dt} + Q_s = P
\]

(35)

where

\[
H = H_s + H_c \geq 0 \quad H_c = \sum_{j = 1}^{N_m} M \left( \frac{dw^{(j)}}{dt} \right)^2 \sum_{\nu = 1}^{N_c} \phi^{(v)} \geq 0
\]

(36)

3. DISCRETE-TIME SIMULATION

Finite difference schemes for the stiff string are covered in detail in \([11]\), and will be reviewed only briefly here.

Assume first a sample rate \( f_s \) (and associated time step \( k = 1/f_s \)), to be employed uniformly across all components in the network. Consider now a single stiff string as defined by \([1]\). The grid function \( u^n_k \) represents an approximation to \( u(x, t) \) at \( t = nk \) and \( x = lh \), for integer \( n \) and \( l \), where \( h \) is the grid spacing. In particular, \( 0 \leq l \leq N \), where \( h = L/N \), for integer \( N \). The discrete domains \( d, d \) and \( d \) are defined as

\[
d = \{0, \ldots, N\} \quad d = \{0, \ldots, N - 1\} \quad d = \{1, \ldots, N - 1\}
\]

(37)

A discrete inner product and norm may be defined over a discrete domain \( b \subset Z \) with grid spacing \( h \) (such as \( d, d \) or \( d \) in \([37]\) above), for grid functions \( f^n, g^n \), as

\[
(f^n, g^n)_b = \sum_{l \in b} h f^n_l g^n_l \quad \|f^n\|_b = \sqrt{(f^n, f^n)_b}
\]

(38)

3.1. Shift and Difference Operators

The forward and backward time-shift operators \( e_{t+} \) and \( e_{t-} \) may be defined, with regard to the grid function \( u^n_k \), as

\[
e_{t+} u^n_k = u^{n+1}_{k} \quad e_{t-} u^n_k = u^{n-1}_{k}
\]

(39)

Forwards, backwards and centered approximations to a first time derivative may be defined in terms of shifts as

\[
\delta_{t+} = \frac{e_{t+} - 1}{k} \quad \delta_{t-} = \frac{e_{t-} - 1}{k} \quad \delta_{t0} = \frac{e_{t+} - e_{t-}}{2k}
\]

(40)

and averaging operators \( \mu_{t+} \) and \( \mu_{t-} \) and an approximation \( \delta_{t0} \) to a second derivative may be written as

\[
\mu_{t+} = \frac{e_{t+} + 1}{2} \quad \mu_{t-} = \frac{e_{t-} + 1}{2} \quad \delta_{t0} = \delta_{t+} \delta_{t-}
\]

(41)

Similarly, spatial shifts \( e_{x+} \) and \( e_{x-} \) may be defined as

\[
e_{x+} u^n_l = u^n_{l+1} \quad e_{x-} u^n_l = u^n_{l-1}
\]

(42)

and approximations to the first and second spatial derivatives as

\[
\delta_{x+} = \frac{e_{x+} - 1}{h} \quad \delta_{x-} = \frac{1 - e_{x-}}{h} \quad \delta_{xx} = \delta_{x+} \delta_{x-}
\]

(43)
3.2. Basic Scheme

A basic explicit finite difference scheme for an uncoupled linear stiff string, as in [1] may be written, for \( u = u^n_l, l \in d \) as

\[
(\rho A \delta t - T \delta x + EI \delta^2 x + 2\rho A \sigma_0 \delta t - 2\rho A \sigma_1 \delta x \delta x) u = 0
\]

Numerical boundary conditions corresponding to (41) are

\[
u^n_0 = \delta x_u u^n_l = 0 \quad l = 0, N
\]

and allow (44) to be well-defined even when applied at or adjacent to the domain end points.

The scheme (44) satisfies an energy balance of the form

\[
\delta t^n_h n^{-1/2} + q^n_n = 0
\]

where \( h_n^{-1/2} \) and \( q^n_n \) are the discrete-time energy function and power loss, respectively, defined as

\[
b_x^n = \frac{2A}{2} \frac{\| \delta x_t u^n \|^2}{\frac{T}{\rho A} + 2 \frac{\| \delta x_t u^n, \delta x \delta x_t u^n \|^2}{\frac{EI}{\rho A}}}
\]

\[
q^n = 2\rho_A \sigma_0 \| \delta x_t u^n \|^2 + 2\rho A \sigma_1 \| \delta x_t \delta x_t u^n \|_d^2
\]

The power loss \( q^n_i \) is non-negative, but the stored energy \( h_x \) is only non-negative under the condition

\[
h^n \geq \frac{1}{2} \left( \frac{T k^2}{\rho A} + 4\sigma_1 k + \sqrt{\left( \frac{T k^2}{\rho A} + 4\sigma_1 k \right)^2 + 16 \frac{EI k^2}{\rho A}} \right)
\]

which is a numerical stability condition for scheme (44) in isolation. Under this condition, the state size may be bounded in terms of supplied energy.

In implementation, scheme (44) is explicit—if the state \( u^n_i \) is written as a column vector \( u^n = [u^n_0, \ldots, u^n_N]^T \), (44) becomes

\[
u^{n+1} = Bu^n + Cu^{n-1}
\]

where \( B \) and \( C \) are sparse \((N + 1) \times (N + 1)\) matrices. See [1] for the construction of these matrices in terms of the various spatial difference operators.

3.3. String with Nonlinear Connection and Excitation

Consider now the simple case of a stiff string under an excitation force and a nonlinear connection, as per (12). A discrete form is

\[
\ell u = -f_n \frac{1}{h} I(x_n) + f_n \frac{1}{h} I(x_n) \quad M \delta t w = f_n
\]

Here, \( f_n \) is a time series representing an approximation to \( f_e(t) \), of a nature to be described shortly, and \( f_n \) is an approximation to the externally-supplied function \( f_e(t) \), perhaps obtained through sampling. The grid functions \( I(x_n) \), selects a given location \( x_0 \). Many choices are possible, but the simplest, and that which will be employed subsequently here, is certainly

\[
I(x_0) = \begin{cases} 1, & l = l_0 \text{ round } (x_0/h) \\ 0, & \text{otherwise} \end{cases}
\]

When multiplied by \( 1/h \), as in (50) above, approximations to the Dirac delta functions from (12) result, where \( x_0 = x_n, x_n \).

The force \( f^n_n \) will be dependent on the relative displacement \( \eta \) of the string and lumped mass at the connection grid index \( l = l_c \).

\[
\eta^n = u^n_{l_c} - u^n
\]

Consider now the inner product of the first of (50) with \( \delta t \), this leads to the energy balance

\[
\delta t^n_h n^{-1/2} + q^n_n + f^n_n \delta t \delta t_v u^n_w = \int_{x_0}^{x_N} f^n_n \delta t \delta t_v u^n_w dx
\]

where \( h_n^{-1/2} \) and \( q^n_n \) are as defined in (47), and where \( p^n_n \) is the discrete input power due to the excitation.

Similarly, multiplying the second of (50) by \( \delta t \), this leads to

\[
\delta t^n_h n^{-1/2} + q^n_n + f^n_n \delta t \delta t_v u^n_w = 0
\]

Adding (53) and (54), and using (52) leads to the balance

\[
\delta t^n_h n^{-1/2} + M \frac{(\delta t^n w)^2}{\delta t^n \eta} + q^n_n + f^n_n \delta t \delta t_v u^n_w = 0
\]

What is lacking is a definition of \( f^n_n \). Here are two:

Here, \( \phi^n_n \) is an approximation to \( \phi \) at time \( t = (n - 1/2)k \), such that \( \phi^n_n \geq 0 \), and \( \psi^n_n \) is an approximation to \( \psi \) at time \( t = (n - 1/2)k \). When inserted in (55) above, either form in (56) leads to the energy balance

\[
\delta t^n h_n^{-1/2} + q^n_n = p^n_n \quad h_n^{-1/2} = h_n^{-1/2} + b^n_n-1/2
\]

where, for the two choices of the force \( f^n_n \) from (50),

\[
\delta t^n h_n^{-1/2} = \frac{M}{2} (\delta t^n w)^2 + \frac{1}{2} (\phi^n_n)^2 \geq 0
\]

Under the further condition (58), then \( b_n \geq 0 \) implying that \( b_n \geq 0 \), and before the system as a whole will be numerically stable.

3.4. Implementation: Iterative vs. Non-iterative Methods

When written in vector/matrix form, the scheme (50) has the form

\[
u^{n+1} = Bu^n + Cu^{n+1} + \theta j_x f^n_c + \theta j_z f^n_c
\]

\[
u^{n+1} = 2w^n - w^{n-1} + k_\ell^n f^n_c
\]

where \( \theta = k_\ell^2 / (\rho A h(1 + \sigma_0 k)) \), and where \( j_x \) and \( j_z \) are \( N \times 1 \) element column vectors, all zero except for a 1 in locations \( l_1 \) and \( l_N \) respectively.

Now, using the fact that

\[
\delta t^n \eta^n = \frac{1}{2k} \left( f^n_c (u^{n+1} - u^n) - w^{n+1} + w^n \right)
\]

and the updates (59) leads to the affine relationship between \( \delta t \), \( \eta^n \) and \( f^n_c \):

\[
\eta^n = \delta t^n + \delta t^n \eta^n + \delta t^n f^n_c = 0
\]
where $\Xi^n$ consists of previously computed (known) values of $u$ and samples of the excitation $f^n$, and $\zeta$ is a constant.

Consider now the first energy-conserving definition of $f^n$, from [56]. In combination with [61], this leads to the nonlinear equation:

$$r + 2k\phi\left(r + \eta^{n-1}\right) - \phi\left(\eta^{n-1}\right) + 2k\Xi^n = 0 \quad (62)$$

where $r = \eta^{n+1} - \eta^{n-1}$ is the unknown. Such a form has appeared in earlier works regarding energy-conserving collision simulation [12, 13], and requires, in general, an iterative solution through, e.g., Newton-Raphson; the number of iterations depends strongly on the particular parameters defining the nonlinearity.

The second form of $f_n$ given in [56] leads to a distinct update. Define

$$g^n = \frac{\delta_t u \psi^{n-1/2}}{\delta_t \eta^{n}} \approx \frac{d\psi}{d\eta} |_{t=nk} \quad (63)$$

The time series $g^n$ can be computed directly from known values of $\eta^n$ and the functional form of $\psi$. Given $g^n$, the following pair of updates results from [61] and [63].

$$\delta_t \eta^{n} + \zeta g^n \mu_t + \psi^{n-1/2} + \Xi^n = 0 \quad \delta_t u \psi^{n-1/2} = g^n \delta_t \eta^n \quad (64)$$

These can be consolidated into a single update yielding $\eta^{n+1}$ from previously computed values of $\eta$ and $\psi$:

$$\eta^{n+1} = \Theta \left( \eta^n, \eta^{n-1}, \psi^{n-1/2} \right) \quad (65)$$

and, given $\eta^{n+1}$, the second of (64) may be updated to yield $\psi^{n+1/2}$, at which point the simulation advances to the next time step. For more details, see [13].

### 3.5. A Complete Discrete-time Modular Network

Returning to the complete modular system presented in Section 2.3, the numerical scheme corresponding to [29] is

$$\ell^{(q)} w^{(q)} = - \sum_{\nu \in I^{(q)}} f^{(q)}_{\nu} \frac{1}{h^{(q)}} I \left( \hat{x}^{(q)}_{\nu} \right) + \sum_{\zeta \in I^{(q)}} f^{(q)}_{\zeta} \frac{1}{h^{(q)}} I \left( \hat{x}^{(q)}_{\zeta} \right) \quad (66)$$

Here, $w^{(q)} = u^{(q)}, n$ is the grid function corresponding to the $q$th string, with grid spacing $h^{(q)}$, and defined over $l \in \{0, \ldots, N^{(q)} \}$ and $\ell^{(q)}$ is the difference operator derived from $L^{(q)}$. $w^{(q)} = u^{(q)}, n$ is the time series corresponding to the displacement of the $q$th string, $j = 1, \ldots, N_m$ and $f^{(q)}_{\nu}$, $\nu = 1, \ldots, N_e$ to the associated connection forces. In (63) above, the time step $n$ accompanying all dependent variables is suppressed for brevity.

Each of the $N_c$ connection forces $f^{(q)}_{\nu} = f^{(q)}_{\nu}, \nu = 1, \ldots, N_c$ is assumed dependent on a displacement

$$\eta^{(q), n} = \eta^{(q), n} - u^{(q), n} \quad (67)$$

There is assumed an underlying discrete potential $\phi^{(q), n-1/2}$ (and accompanying function $\psi^{(q), n-1/2}$), such that, for the non-iterative algorithm,

$$f^{(q)}_{\nu} = \mu_t + \psi^{(q), n-1/2} \frac{\delta_t u \psi^{(q), n-1/2}}{\delta_t \eta^{(q), n}} \quad (68)$$

Full details of the implementation and energy analysis will not be presented here, because of space limitations, but follow in almost all respects from the analysis of the single string/connection described in the previous section. A demonstration of energy conservation appears in Section 4.1 and of the benefit of a non-iterative algorithm, in terms of computation time, in Section 5.

### 4. SIMULATION RESULTS

In this section, we present some numerical results illustrating numerical and musical aspects of the modular system described here. All simulations are run at 44.1 kHz.

#### 4.1. Energy Conservation

Consider first the energy conservation property, for a full network of 25 strings (ranging in pitch from C2 to C4), and using 24 two-sided connections, where the non-iterative scheme is employed. A worst case is assumed here, where the strings are lossless, and the initial conditions of the strings and lumped elements are randomised. In Figure 5, the energy partition as a function of time between strings and connections is shown, alongside the normalised energy variation, illustrating energy conservation to machine accuracy. The availability of such a measure allows for an excellent approach to debugging modular synthesis codes.

Figure 5: Left: energy partition, showing energy in strings, connections, and the total. Middle: normalised sample to sample energy variation, and right: a detail showing energy conservation to machine accuracy.

#### 4.2. Single String/Lumped Object

An illustration of the interaction between a single string and a lumped object in intermittent contact is shown in Figure 6. Even in this extremely simple case, a wide variety of timbres is possible. In Figure 7, spectrograms of sound output are shown where string parameters are chosen according to a high E string on a guitar.

#### 4.3. Large network

Consider now a network of 25 strings with 24 double-sided connections, representing approximately the largest possible in real time at 44.1 kHz. Snapshots of the time evolution of this network are shown in Figure 8.

### 5. COMPUTATIONAL ANALYSIS

This section details the computational costs of the element types (stiff string and connection) from which the system is built. We
start with a set of strings, and then compare an individual non-linear connection solver in both iterative and non-iterative form. Finally we assess a full system of strings and connecting elements, as could be used in a real-time audio plug-in. All simulations are written in C++, and timings are produced by running at a sample rate of 44.1 kHz (in double precision) over 441,000 time steps and then dividing by 10 to give an average performance for 44,100 steps. The test CPU is a 6-core Intel Xeon E5-1650 v2, and the LLVM compiler was used. Whilst we will not consider multi-threading here (as this presents problems for real-time usage) we do make use of vectorization, namely with Intel’s SSE and AVX intrinsics [25].

The stiff string is simulated using the scheme (44), which is explicit, and amenable to spatial parallelization. The state size and computational cost can become large, but not unmanageably so: for the case of 25 low-pitched strings tuned from C2 at 65Hz to middle C4, the total state size required is 2,550 values. Table 1 shows results using various compiler optimisation levels, and also using manually written vector intrinsics which lead ultimately to a speedup by a factor of four. Performance is faster than real time.

Table 1: Computation times for 25 strings, tuned from C2 to C4, for 1 s output. Total state size: 2,550 grid points.

<table>
<thead>
<tr>
<th>Optimisation Level</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-O0</td>
<td>0.59</td>
</tr>
<tr>
<td>-O3 SSE only enabled</td>
<td>0.18</td>
</tr>
<tr>
<td>Manual AVX</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Raphson solver, and then a form which uses the new non-iterative solver. For the purposes of this testing the Newton-Raphson solver was run for 10 iterations at each time step, starting from a cached solution. This is a usable “average” figure for the simulation, although in practice could be larger, and also possibly reduced by testing for a residual.

The algorithm for solving for each connection force consists of some initial arithmetic operations and two calls to the \texttt{power()} function with non-integer exponents (using \texttt{std::pow()} from the cmath library). Then the Newton-Raphson solver is launched. This requires a further two calls of the \texttt{power()} function at each iteration. Finally there are some further arithmetic calculations to compute the forces at each end of the connection. The non-iterative form is considerably simpler, requiring just two \texttt{power()} functions in total. Table 2 shows the resulting computation times. The benefit of the non-iterative form is clear, giving a $11 \times$ speed up over the iterative form. This is mostly due to the reduction in the number of calls to the \texttt{power()} function, from 22 in the iterative form to just two in the latter. Further optimisation may be
achieved by implementing a manually vectorized power function across groups of connection calculations.

The final test simulation involved two octaves of strings with 24 two-sided rattle connections, such that each string was connected to another through a lumped element—a single strike to any string will excite the entire network, as in Figure 8. At each time step the strings are updated first, followed by a loop over the connections which then adds back the calculated forces into the strings at the connection points. Table 3 shows the results for the full system.

<table>
<thead>
<tr>
<th>Optimisation</th>
<th>Iterative (s)</th>
<th>Non-Iterative (s)</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>-00</td>
<td>2.53</td>
<td>0.81</td>
<td>3.1×</td>
</tr>
<tr>
<td>-03 SSE</td>
<td>1.93</td>
<td>0.35</td>
<td>5.5×</td>
</tr>
<tr>
<td>Manual AVX</td>
<td>1.84</td>
<td>0.28</td>
<td>6.6×</td>
</tr>
</tbody>
</table>

The version computed using an iterative solver results in a best time of 1.84 s for 1 s sound output, which is clearly well short of the real time threshold. The non-iterative solver results in a 6.6× speedup, and the resulting time of 0.28 seconds is just within the scope of usability for a real-time application. Note that performance levels may vary according to other factors such as the CPU-specific cache, and other compiler details.

### 6. CONCLUDING REMARKS

A form of this system available as a real-time plug-in is under development through Physical Audio [26], called net2. It is rewritten from a previous version (called net1), which ran offline in multicore using an iterative solver. The ability to sidestep such iterative methods, and maintain a numerically-stable synthesis algorithm has allowed this move to real time through the approximately 10× speedup for the nonlinear part of the simulation. Though only stiff strings have been shown here, the extension to systems including multiple vibrating plates is immediate—see, e.g., [5]. Also, only one type of nonlinearity has been presented here, but the non-iterative algorithm presented here is fully general.

A major consideration, at the level of the user experience, is in the UI design, particularly when there are potentially many stiff string/connection elements to manage—this has been partly dealt with during the design of the simpler Deralier system, also from Physical Audio. A deeper issue is that of exploring the design parameter space—for the system illustrated here with 25 strings and 24 connections, for example, there are 319 parameters to set. Some heuristics can be employed to make this more manageable (by, say, restricting string tunings), but clearly some more general strategy for finding interesting regions of the parameter space (perhaps invoking methods from machine learning) is necessary.

### 7. REFERENCES