The Geometric Oscillator: Sound Synthesis with Cyclic Shapes

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ABSTRACT

From perfect circular motion derives the sine wave. Deforming the circle or replacing it by a different cyclic shape produces a different waveform. This marks the conceptual basis of the *geometric oscillator*. Interaction with the shapes, such as in a graphics editor, becomes interaction with the timbres that derive from them. In this paper, we elaborate on this synthesis method, introduce a further derivation step that comes with some handy advantages, and detail a corresponding user interface approach. A prototype implementation, called Cyclone, is described. Based on feedback that we gained from demos and our own experiences from experiments we will outline the next iteration of Cyclone's further development.

CCS CONCEPTS

• **Human-centered computing → Sound-based input / output**; *Human computer interaction (HCI)*; *Graphical user interfaces*; • **Applied computing → Sound and music computing**;

KEYWORDS

Sound Synthesis, Geometric Oscillator, User Interface

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1 INTRODUCTION

Making sounds and music is a basic form of human expression. Through experimentation, children learn early on which events produce which sounds. An important aspect of this learning process is that the child relates auditory perceptions to other sources of sensory input. With time, an individual develops the ability to predict the sound of hitting an object, plucking a string or striking a key on a piano. Information about the material, shape and state of physical objects is used to create estimates of the sounds they will make when interacted with.

In the digital domain, the characteristic variations of air pressure responsible for an auditory perception are represented as sequences of numbers. Thus, synthesizing a sound at its most basic level comes down to generating this sequence. Theoretically, every perceivable sound can be described by typing in every sample value one by one. But apart from the fact that this implies an impractical typing effort, this method also requires the user to know the exact wave shapes of the sounds to be generated:

> "It is not enough to know in theory that any sound can be produced. You need tools to derive the proper parameter values from a specification of a desired result." [5]

Digital synthesis methods can provide embedded knowledge, abstractions and constraints that facilitate the generation of a specific range of sounds. This allows the user to think about sound generation in other terms than sequences of numbers.

In this paper, we present a sound synthesis method that derives its waveforms from cyclic Bézier curves. These shapes constitute the interface for both users and automation. Users can directly interact with the shapes, deform them to change the sounds generated, assign modulations or MIDI controllers to sections of the shape and steer them directly or through automation. The shapes' mapping to waveforms translates visual angularity to timbre. Smooth shapes create dark timbres, sharp angles produce timbral sharpness.

The following sections will expand on this sound synthesis and interaction method and present a prototype implementation called Cyclone. We start with a summary of related work in section 2. The Cyclone sound synthesis and graphical user interface are then detailed in sections 3 and 4, including respective critical discussions. Section 5 provides an outlook

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on the next development iteration of Cyclone which will become commercially available as iOS app by end 2017 (and later as VST/AU plugin). Section 6 concludes this paper.

2 RELATED WORK

Still today, many (especially commercial) software synthesizer applications mimic the interface of their analog hardware predecessors. These interfaces emulate the typical control surfaces comprised of physical knobs, faders and buttons.

> "In spite of the migration that the industry has seen from hardware to software over the last 20 years, the user interface of the typical synthesizer is, in many respects, little changed since the 1980s and presents a number of usability issues. Its informed use typically requires an in-depth understanding of the internal architecture of the instrument and of the methods used to represent and generate sound." [18]

Different approaches tackle this issue in likewise different ways. In the following, we will focus on those that are conceptually related to the Cyclone approach, i.e. approaches that are based on a geometric relation between the interactive visuals and the waveform generated.

The idea of visualizing the waveform of the sound to be synthesized and making this visualization interactive to edit the sound has lead to numerous *waveshaping* synthesizers. Here, the values in a wavetable can be edited by the user, either directly or through transfer functions. This is a comparatively inconvenient way of defining sounds, especially when it comes to modulations, i.e. variations of the values in the wavetable or morphing of the transfer functions over time. *Bézier synthesis* [6] is an approach that makes such modulations easier. The waveform is modelled by a cubic Bézier curve. Changes to the waveform are achieved by moving the control points. Hence, the control points introduce a level of abstraction that makes user interaction and modulations easier.

The concept of *wave terrain synthesis* [12] extends the idea of wavetable synthesis using a 2d scalar field that implicitly defines the set of available waveforms. One particular waveform can be picked from it by defining a trajectory, so-called *orbit* [17], across the terrain. This orbit can be manipulated over time which causes changes in the waveform and, hence, spectral changes. The visuality of this approach can easily be utilized for graphical user interfaces such as demonstrated by the waveTerrainSynth [1] and the *Max for Live* plugin WAVE [19].

The Wablet [20, 21] is another attempt to visually interact with the synthesis method. It utilizes a synthesis algorithm originally developed by Verplank et al., called *scanned synthesis* [22]. This algorithm is based on a physical model of a string or membrane, i.e. a vibrating dynamic system. Vibration is typically below audio rate and specifies the modulation of the sound over time. The system is scanned periodically at audio rates to generate sound. Tubb points out, this method is a form of wavetable/wave terrain synthesis with a periodically updated table that derives from the displacement of the mass elements in the model [20]. Verplank et al. emphasize that the possibility to directly manipulate the dynamic system through sensors is a major advantage of the method. The Wablet facilitates this by visualizing the system on a multitouch screen, giving the user the opportunity to influence the vibration via touch input.

The concept of *geometric oscillators*, that constitutes the core of the Cyclone approach, has already been applied by Leahy in his SuperCollider tool named SCREAM [8]. It interprets a circular shape as complex oscillation. In the following sections, we will redefine this concept, extend it and develop a user interface approach that allows for direct interaction with the shapes.

3 CYCLONE SYNTHESIS

With Cyclone we define the concept of the *geometric oscillator*, i.e. an oscillator that derives its wave output from a cyclic two-dimensional path, here implemented as Bézier path. Our prototype implementation uses two such oscillators that are specified by the free-form Bézier shape and by the parameters pitch, detuning and amplitude. The shapes' control points and the additional parameters can be modulated by several ADSR envelopes, low frequency oscillators and MIDI control messages.

Geometric Oscillator

Cyclone's sound generation algorithm is rooted in geometry, in particular in circular motion and the projection of this motion onto a line. This is known as complex oscillation. Figure 1 shows a point Q in two dimensional space, that moves along a circle path centered around the origin, at constant speed or in the digital domain at constant step width, respectively. Let Q' be the projection of Q onto the y-axis. Then Q' performs a harmonic oscillation that equals a sine wave, when plotted along the axis of time. The sine wave is considered to be the most basic waveform, since it does not contain any additional harmonics.

Let the circle be represented by four cubic Bézier segments. This does not reproduce a perfect sine wave, since cubic Bézier curves cannot represent a perfect circular arc. But the approximation is good enough so that most users will effectively not perceive a difference, i.e. higher frequency content is very low (SNR $\geq$ 70dB). If the circle is transformed, e.g. by moving one of the control points, the produced wave shape

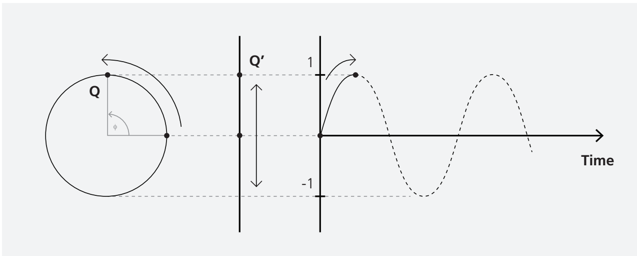


Figure 1: Sine wave derived from circular motion.

changes, causing an audible change to the timbre generated. The user can add further control points, i.e. subdivide the shape into smaller Bézier sections, and create more complex shapes.

To calculate the waveform, i.e. filling a wavetable with sample values, the Bézier path is periodically scanned at a given frequency. This requires the sampling points on the shape to be equidistant and, hence, a re-parameterization of the Bézier curve, see [14]. Different approaches can be found in literature [2–4]. In Cyclone, Gravsen's recursive approximation approach is applied [3].

In its first implementation, the synthesis algorithm evaluated each point along the path and directly used the normalized y-coordinate as sample value. This naïve approach has the serious downside, that changes along the x-axis affect the sound substantially less than changes along the y-axis. As a result, some shapes may look very different but produce very similar waveforms. An example of this is shown in figure 2(a).

To deal with this problem, another way of deriving the waveform from the shape was introduced. Instead of using the normalized y-values, the unit normal vector is computed at every evaluation point. The height of this unit normal vector is then used as sample value. This leads to a number of advantages compared to the naive method:

- It leads to a more uniform relation between shape and sound, with changes in x- and y-direction resulting in a proportionate degree of change in the waveform and perceived sound.
- To model waveforms such as square waves, the Bézier path had to contain discontinuities, i.e. jumps. With our second method, discontinuities in the waveform are achieved by discontinuities in direction, i.e. angles. As a result, these sounds can now be expressed without having to introduce jumps as an additional modelling functionality for the circular path.
- As seen in figure 2(a), different shapes may result in very similar waveforms with the first method. With the new method, figure 2(b), a loop in the path always results in a different waveform than a notch or bulge.

Modulation

When scanned, the cyclic path produces a strictly periodic waveform, similar to the oscillators of a subtractive synthesizer. To produce convincing timbres, the waveform has to be modulated in some way to enable spectral changes over time, which are well-known as an important characteristic of interesting timbres [15, 16]. To enable this, the prototype has a number of modulation units. Each unit can be defined as an ADSR envelope or a low frequency oscillator. MIDI controllers constitute a further modulation source.

Each can be assigned to control points of the shape, or the three additional parameters pitch, tuning and amplitude. While the modulation of the additional parameters is well-known from other synthesizers, the modulation of the control points is special. When assigning a modulator to a control point, a trajectory is defined and can be edited by the user. In the prototype implementation these trajectories are linear. The modulator lets the control point move along this modulation path according to the modulator's waveform. One modulator can be assigned to several control points, each with its own trajectory. In this way, complex sound transformations can be achieved.

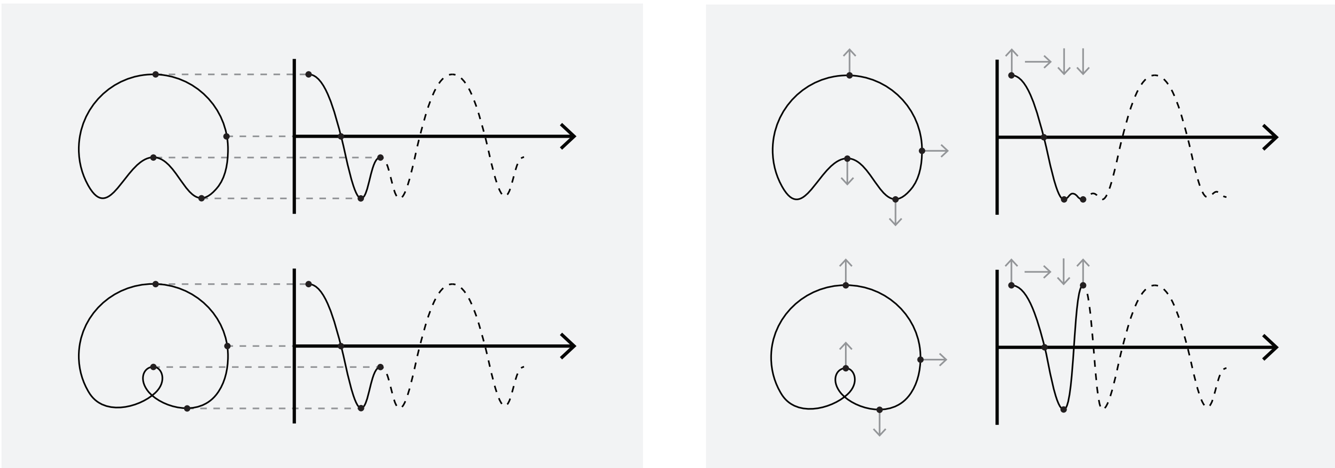
Discussion

All timbres derive from strictly circular motion. Hence, the overtone spectra are all harmonic. Dissonant spectra require time-variant shapes with a more complex behavior that is difficult to achieve with the possibilities of modulation so far. Instead, the prototype implements a second geometric oscillator so that both can be detuned against each other.

C^2 continuous shapes create C^1 continuous waveforms, i.e. sounds with few harmonics. Points on the shape that feature only C^1 or C^0 continuity create corners or, in the latter case, discontinuities in the waveform. These feature a richer overtone spectrum creating bright and sharp timbres. This intuitive connection of smoothness/sharpness in the geometric shape as well as in the corresponding sound is one of the great advantages of Cyclone's geometric oscillator concept.

Bézier shapes are easy to use. The control points are comfortable handles with which entire curve segments can be formed. However, each deformation, i.e., each update of the Bézier shape requires a re-parametrization. This is a rather expensive step in terms of computational performance which in turn limits the polyphony of the synthesizer.

As an alternative to Bézier curves, we also experimented with polygons. However, these have no control points. Moving an individual vertex of a polygon has only a local effect to the adjacent edges. The effect does not propagate over a



(a) Version 1 uses the normalized y-coordinate as sample value.

(b) Version 2 uses the height of the unit normal vector.

Figure 2: Both versions of the geometric oscillator.

larger curve segment. Accordingly, other interaction mechanisms are necessary. Spring-mass models may be used to reproduce a behavior similar to Béziers.

4 CYCLONE INTERFACE

The motivation for the development of Cyclone is to find a more visual approach to sound synthesis. This is achieved by using cyclic Bézier paths as mathematical foundation of the synthesis method. Apart from three faders for pitch, tuning and amplitude for each oscillator, the prototype contains no traditional hardware emulating controls such as knobs and faders. It relies mainly on editing the Bézier paths and applying modulation to individual control points as an interface to timbre design.

Designing Timbres Through Shapes

Cyclone's graphical user interface (GUI) is shown in figure 3. This is not the place where the instrument is played, such as in The Wablet [20, 21]. It is rather the environment where the user designs the sounds. The synthesizer is then played via its built-in MIDI interface. The upper half of the GUI contains the two geometric oscillators. Right below are two waveform displays, showing the corresponding waveforms. On the bottom are the four modulation units which can be configured to be either an envelope or low frequency oscillator. The bottom line holds the MIDI controllers.

For the interaction with the Bézier path, we follow the same concept that is established in literally every graphics editing software and, thus, well-known. The control points are presented as handles that the user can move around and, thereby, edit the path of the corresponding segment of the path. Two neighboring segments share one point (ending point of one segment and starting point of the next). To ensure C^2 continuity the two neighboring control points are, by default, placed so that all three points are in alignment with each other and equidistant. Hence, moving one of the neighboring control points of a connection point causes the other neighbor to perform the same movement mirrored. C^2 continuity ensures smooth connections between the Bézier segments and, thus, smooth wave shapes. If the user wants to produce sharper sounds, i.e. waveforms with only C^1 or C^0 continuity it is possible to unlock the link of the connection point and its two neighbors. Now, the user can create sharp peaks and the like.

The Bézier path can be subdivided by clicking on the path. This creates a new connection point and the corresponding neighboring control points. Subdividing the path allows for the construction of more complex shapes and fine-grained modulations.

The modulation units are displayed as ADSR envelope shapes and LFO waveforms. Handles to edit the shapes are located directly at these shapes. Each modulation source has a color-coded circle icon that can be dragged to one or more modulation targets, i.e. the control points and sliders for pitch, tuning and amplitude. When dragged to a control point a linear trajectory is created indicating the movement path that the point will follow when modulated. Their direction and length can be edited by the user through respective handles at the two extremes of the trajectory. When a note is played, the modulations on the Bézier shapes are visually animated. So the user can comprehend and learn the connection between geometric shape, waveform and timbre.

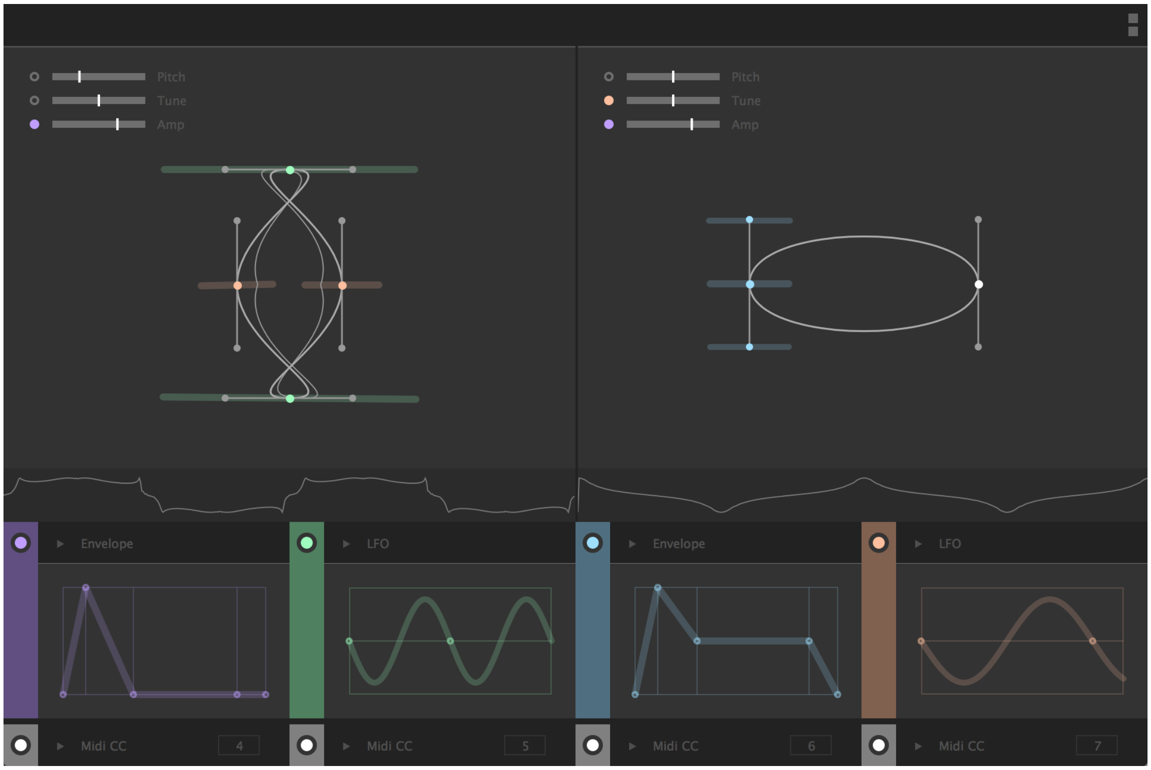


Figure 3: Cyclone’s graphical user interface.

Discussion

The Cyclone synthesizer has been demonstrated at open-house events, a faculty convention, several internal demo sessions, and received an award at *MIDI Hack Stockholm* in 2014. Even though this is no formal user study we could learn a lot from the feedback we gained. Working with the visual shapes to shape the sound is perceived as a more direct interaction than setting numeric parameters with knobs, sliders and the like (such as in modular synthesizers). This can facilitate ease of use and a low learning hump. The interface concept deliberately omits textual and numeric elements. This should help the user to focus on the sound output and work with the shapes on this basis instead of being too focussed on exact numeric values [9, 13].

Even though the prototype is implemented for mouse input the interaction concept can be applied to touch input as well, requiring only larger handles to account for the fat-finger problem. However, creation of increasingly complex shapes in the geometric oscillators and their fine-tuning can become a fiddly task. At this point, the interaction concept does not transfer well to touch devices.

In contrast to the geometric oscillators, the representation of envelopes and low frequency oscillators follows that established in traditional synthesizers. Although the user interacts directly with the modulation curves, their time-amplitude representation is a conceptual break to the geometric oscillators. Alternative representations were examined by Meerpohl [11]. Some of these were adopted by the Magix Audio Remote app [10].

5 NEXT ITERATION AND FUTURE PERSPECTIVES

The next iteration in the development process, called Zykloid, addresses several of the aforementioned issues. Instead of Bézier curves it utilizes polygons which eliminates the expansive re-parameterization step in the scanning process and greatly reduces the scanning function’s need for processing power.

Polygons with up to several hundred vertices, however, require a different interaction approach. Polygons have no control points. Editing the polygons vertex by vertex is tedious and impractical. In Zykloid, the user has several alternative possibilities for defining shapes. The user can draw shapes via touch gestures. Zykloid further offers a series of trochoid presets [7]. Further shapes can be imported from SVG files. In editing mode, the user can apply deformations by pushing or dragging single vertices while cubic interpolation continuously smooths out the shape. Different shapes can be combined by morphing them into each other which produces spectral transitions. Control signals (envelopes, LFOs, MIDI controllers) can be assigned to these morphings allowing for rich and versatile timbres that can be further refined by filters. For the creation of inharmonic spectra a linear frequency shifter and a noise oscillator have been added.

A fully-fledged iOS App (and later a VST/AU Plug-in) of the described synthesis and interaction technique are currently under development and will be commercially available by the end of 2017.

6 SUMMARY

Digital audio synthesis is defined as the process of generating a stream of audio samples from a set of parameters. To make the process of defining and editing sounds more convenient, synthesizer interfaces provide abstractions that break the process down into parts, reducing the amount of parameters that need to be explicitly defined. A broad variety of methods exists. Some are concerned with providing intuitive, easy to use parameters, for instance by using a parameterization that is oriented towards the language musicians use to describe sounds, instead of using technical terms of the synthesis method. Others try to find new representations and visualizations for the structures underlying the synthesis algorithm.

The Cyclone synthesis method proposed in this paper falls into the latter category. More precisely, the Cyclone approach derives its visual interface (cyclic shapes) directly from the waveform. The user interacts with the shapes, the waveform (wavetable) is updated correspondingly. We have described two mapping variants, the first interprets the circular motion along the shape as complex oscillation and projects this motion on a line, the second uses the slopes of the normal vectors instead to construct the waveform. The cyclic shapes are composed by cubic Bézier curves. Their control points are convenient handles to edit the shape manually or via modulation. Cyclone's mapping approach features an intuitive correlation of smooth/jagged shapes and soft/sharp sounds.

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