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**Title:** Computed fingertip touch for the instrumental control of musical sound with an excursion on the computed retinal afterimage  
**Issue Date:** 2015-11-04
3. New systems for computed fingertip touch

In this chapter, we present two systems for computed fingertip touch: one expanding from the cyclotactor (CT) device, and another expanding from the kinetic surface friction transducer (KSFT) device.

The CT system offers a fingerpad distance input with a range of 35.0 mm, a resolution of 0.2 mm, and a sampling rate of 4000 Hz. Simultaneously, it offers a fingerpad force output with a range over distance that is shown in Figure 3.2, a resolution of ± 0.003 N, and accurate wave output up to 1000 Hz. The latency between the input and output is 4.0 ms.

The CT system provides excellent support for real-time instrumental control of musical sound; moreover, its output covers the frequency ranges involved in fingertip vibration perception; and its I/O is capable of inducing aspects of haptic perception.

The KSFT system offers a fingerpad displacement input along two planar directions, with a range of tens of cm, a resolution of 0.02 mm, and an average sampling rate of 125 Hz. Simultaneously, it offers a fingerpad kinetic friction output with a range of 0.14-1.43 N, and with a temporal resolution between 1 and 10 ms. The average latency between input and output here is 20.5 ms.

The KSFT system supports inducing aspects of fingertip surface texture perception during active touch. For fingertip movement at lower speeds and accelerations, I/O can cover the spatial range of surface roughness perception.

The I/O of both systems can be programmed via classes implemented in the SuperCollider language. Using this language also enabled complete integration with computed sound: Input from motor activity, output to somatosensory perception, and output to auditory perception are easily combined within a single written algorithm. Finally, both systems are cheaply mass-producible.


De Jong S, 2010e The cyclotactor. Best Demonstration Award. The 2010 EuroHaptics international conference (July 8-10 2010, Amsterdam, the Netherlands).
3.1 Introduction

In this chapter, we will pursue the second set of goals identified in Section 1.6.9. This means expanding the new transducer technologies of Chapter 2 to new systems for computed fingertip touch – which should algorithmically represent transducer state using physical units; integrate computed sound; support real-time instrumental control of musical sound; and be powerful while cheaply mass-producible.

In Section 3.2, we will pursue these goals for the cyclotactor (CT) device; in Section 3.3, for the kinetic surface friction transducer (KSFT) device. The resulting CT system won Best Demonstration Award at the international EuroHaptics conference of 2010 [De Jong 2010e].

3.2 The CT system

3.2.1 Technical capabilities

3.2.1.1 Distance input in mm  The way in which accurate and linear fingerpad-to-surface distance input was obtained for the CT device corresponded to obtaining an algorithmic representation of transducer input in terms of millimeters (see Sections 2.2.4.3 and 2.2.5.3). This representation had a range of 35.0 mm, a resolution of 0.2 mm, and a sampling rate of 4000 Hz (see Section 2.2.7.2).

3.2.1.2 Force output in N  For transducer output, the physical unit chosen for algorithmic representation was the force, in newtons, applied orthogonally to the human fingerpad via the keystone permanent magnet. After obtaining a final design of keystone and electromagnet which included accurate and linear magnetic field strength output (see Section 2.2), more work was needed to obtain a force output in N.

With the keystone permanent magnet aligned straight above the electromagnet core, measurements were made to determine how applied orthogonal force varied over coil current and distance above device surface. This was done using a device custom-built for the purpose, which allowed precisions of 0.005 A, 0.01 mm, and 0.01 N.

Part of the resulting measurements are shown in Figure 3.1. At the back, it can be seen how a fixed current of 10 A results in an upward force, which diminishes over distance. This decrease follows a curve, which is also represented by the green coloring becoming ever lighter over distance. At the front, it can be seen how a fixed current of 0 A results in a downward force, which also diminishes over distance, represented by red coloring becoming ever lighter.

Between the front and back of Figure 3.1, however, it can be seen how the force curves for fixed currents between 0 and 10 A may first increase, then decrease over distance. Also, the coloring shows how here, the same fixed current may result in a downward as well as an upward force, depending on the distance. Such a perceptually different result illustrates how it would be a pitfall to regard the volts or ampères of the coil circuit – although they too describe transducer state – as sufficient physical units to algorithmically represent transducer output.
Figure 3.1 The CT system: measurements underlying fingerpad-orthogonal force output in newtons.
The blue curve in Figure 3.1 highlights where a force of 0 N is applied. This curve has been duplicated on the graph floor, to show more precisely the current required over distance. Only after using this characteristic, to counteract magnetization of the electromagnet core by the keystone, did it become possible to have the CT device appear like an ordinary, inactive surface.

To enable this, and more, a DSP algorithm was written which took a requested force in N as input, and then computed the required coil current based on the distance input and interpolation tables derived from the measurements just discussed. Using this algorithm to control the coil circuit, a force output in N was implemented. The output range, varying over distance, is shown in Figure 3.2.

![Figure 3.2](image)

**Figure 3.2** *The CT system: force output range over distance.*

![Figure 3.3](image)

**Figure 3.3** *The CT system: magnetic output frequency response.*
Based on the force output range at device surface, and the amplitude resolution discussed in Section 2.2.4.7, the amplitude precision of force output was estimated at 0.003 N. The temporal resolution when controlling magnetic field strength to produce force output allowed accurate wave output across the 0-1000 Hz range (see Section 2.2.5.5). The attenuation of this wave output, measured over frequency, is shown in Figure 3.3. As can be seen, over the 0-400 Hz range – important for inducing aspects of fingertip vibration perception – attenuation is linear and, with a dip of 5%, approaches a flat response.

3.2.1.3 I/O latency in ms The latency achieved between the above distance input and force output was 4.0 ms (see Section 2.2.7.2). This enabled inducing aspects of haptic perception.

3.2.1.4 Integration with computed sound During transducer development, described in Section 2.2, the software components of the CT device were made in the Max/MSP programming environment. However, after completion of prototype 4, when creating algorithms for the CT device that also incorporated computed sound, I/O failed. This was found to be caused by DSP computations being dropped in Max/MSP. All software components were then ported to the SuperCollider programming language [McCartney 2002], which did not present this problem. Also, the SuperCollider programming libraries supported the implementation of all types of computed musical sound discussed in Section 1.4, in any combination algorithmically possible. Additional classes were written to provide access to the CT I/O discussed in the Sections above. After this, algorithms could be written in SuperCollider which, apart from output to auditory perception, also included input from motor activity, and output to somatosensory perception. An example of this will be given in Section 3.2.2 below.

3.2.1.5 Real-time instrumental control of musical sound When making music in real time, for human control to be satisfying, the latency between sensor input and audio output should be at most 10 ms, according to [Wright 2002]. To this end, voltage I/O in the CT system was implemented using the Motu UltraLite mk3 interface of prototype 4, controlled using OS X Core Audio (see Section 2.2.6.1). This resulted in a latency from distance input to (headphone) audio output of 3 ms, well below the stated limit.

3.2.2 Programming interface As discussed above, the software components of the CT system were re-implemented in the SuperCollider language. In addition to this, a class library was written which provided DSP primitives usable for both computed sound and computed touch. On the one hand, this library served as a wrapper providing access to a range of synthesis primitives via a single uniform syntax. On the other hand, its implementation added precise and accurate control over amplitude and phase, important for forms of parametrized waveform generation.

In Figure 3.4, a code example using the implemented CT I/O class is shown. This example also illustrates the integration, within a single algorithm, of input from human
motor activity, output to human auditory perception, and output to human somatosensory perception.

3.2.3 Cost and mass-producibility The hardware components of the CT system can be divided into an off-the-shelf personal computer; an off-the-shelf electronic signals interface; and the custom transducer electronics. The personal computer and signals interface used were both mass-produced, costing € 400 and € 500, respectively (in 2014; for other details, see Section 2.2.6.1). All of the custom transducer electronics are mass-producible as well (see Sections 2.2.4.1, 2.2.5.1, and 2.2.6.1). However, especially the cost of the coil circuit was an open question.

Figure 3.4 The CT system: code example. Highlighted in blue: regular audio output. Highlighted in green, from top to bottom: distance input in mm, force output in N.
After CT prototype 4 had been completed, Arno van Amersfoort of the Electronics Department at the Leiden Institute of Physics [ELD 2014] designed and built a miniaturized version of the coil circuit, using newer and cheaper components. Testing this circuit then confirmed that it indeed matched the original circuit in terms of the parameters of force output and I/O latency discussed in the preceding Sections. The new circuit also meant that a desktop form factor for the custom transducer electronics now would need a volume at most the size of a pizza box. The unit cost of the new coil circuit, like the unit cost of the other transducer electronics taken together, would be less than € 400.

Therefore, in summary, the hardware components of the CT system are mass-producible, at a cost (excluding the host laptop computer) below € 1300.

3.2.4 Research goals attained in the resulting system  In the preceding subsections of Section 3.2, we have presented the CT system for computed fingertip touch. How, in summary, have the chapter goals identified in Section 1.6.9 been achieved in this system?

The first goal was to algorithmically represent transducer state using physical units. In the CT system, this is done using a distance input in mm, a force output in N, and a known latency in ms between the two (see Sections 3.2.1.1 to 3.2.1.3). The programming interface for writing algorithms that use this I/O has been discussed in Section 3.2.2.

The second goal was to integrate computed sound. In the CT system, this has been done through use of the SuperCollider programming language (see Section 3.2.1.4). The code example given in Section 3.2.2 illustrated the resulting, complete integration.

The third goal was to support real-time instrumental control of musical sound. In the CT system, the latency between input from motor activity and output to auditory perception is more than sufficiently small to achieve this goal (see Section 3.2.1.5).

The fourth and final goal was to realize a powerful, yet cheaply mass-producible system.

Here, we understand implementations of computed fingertip touch to be more powerful, if characteristics such as automaton processing speed, memory size, and transducer fidelity enable inducing a wider range of perceptual phenomena (see Sections 1.6.7 and 1.4.4). The CT system, then, can be regarded as powerful because its performance enables satisfactory real-time instrumental control of computed musical sound (see Section 3.2.1.5); because its force output covers the frequency ranges involved in fingertip vibration perception (see Section 3.2.1.2); and because its I/O latency enables inducing aspects of haptic perception (see Section 3.2.1.3).

Finally, we understand a system for computed touch to be cheaply mass-producible if large-scale production is possible at a cost comparable to that of common, widely used devices for personal computing. As discussed in Section 3.2.3, the CT system,
excluding the host personal computer, is mass-producible at a unit cost below that of a mid-range laptop computer.

3.3 The KSFT system

3.3.1 Technical capabilities  

3.3.1.1 Displacement input in mm  
The way in which surface-parallel fingerpad displacement tracking was implemented in the KSFT device corresponded to obtaining an algorithmic representation of transducer input in millimeters (see Section 2.3.4.2). Here, the values due to individual sensor updates were accumulated over time, resulting in a displacement input representing relative position rather than velocity. This representation had a range of tens of cm in both planar directions, a resolution of 0.02 mm, and an average sampling rate of 125 Hz (see Section 2.3.5.2).

Because the sampling rate of displacement input was much lower than the rates for friction and audio output, its use could lead to perceivable quantization artefacts in the output to somatosensory and auditory perception. To counter this where necessary, a variant of the displacement input was implemented, providing an approximate reconstruction of the displacement trajectory at a higher temporal resolution. This was done using linear interpolation over the average update interval. Cubic spline and sinc interpolation were considered, also, but as these required more data points than just the current and previous displacement update, they were not used, to avoid adding extra latency. For the same reason, a mechanism to resynchronize with the sensor hardware update clock was left out, as well (see Section 2.3.4.2).

3.3.1.2 Friction output in N  
For the algorithmic representation of transducer output, the physical unit chosen was the kinetic friction, in newtons, applied to the moving puck. Via the puck contact surface, this corresponded to the force applied, in a parallel direction, to the moving human fingerpad. Measurements were made to determine how kinetic friction varied over coil current. This was done using a device custom-built for the purpose, which allowed precisions of 0.005 A and 0.01 N. The resulting measurements are shown in Figure 3.5.

Using these measurements, a DSP algorithm was written which implemented a kinetic friction output in N. The range obtained for this output was 0.14-1.43 N. This meant that the KSFT system covered the 0.15-0.42 N friction range recommended in [Crommentuijn and Hermes 2010] for haptic devices operated by the fingers and wrist. For the shortest effective features in friction output, a duration between 10 ms and 1 ms was obtained (see Section 2.3.5.2).

3.3.1.3 I/O latency in ms  
The average latency achieved between the above displacement input and friction output was 20.5 ms (see Section 2.3.5.2). This did not enable inducing aspects of haptic perception, but did enable inducing aspects of fingertip surface texture perception during active touch.
3.3.1.4 **Integration with computed sound** The software components of the KSFT device, like those of the CT device, were ported to the SuperCollider programming language. Classes were written to provide access to the KSFT I/O discussed in the preceding Sections. After this, algorithms could be written in SuperCollider which, apart from output to auditory perception, also included input from motor activity, and output to somatosensory perception. An example of this will be given in Section 3.3.2 below.

3.3.1.5 **Real-time instrumental control of musical sound** Due to the input stages of the KSFT device, the average latency between displacement input and (headphone) audio output was 19.5 ms (see also Section 2.3.4.4). This was well above the 10 ms limit already discussed above, and when making fast changes to heard musical sound, the delay could become noticeable and unsatisfactory.

3.3.2 **Programming interface** As discussed above, the software components of the KSFT system were implemented in the SuperCollider language. Here too, the custom class library providing DSP primitives for both computed sound and computed touch could be used when writing algorithms.

In Figure 3.6, a code example using the implemented KSFT I/O class is shown. This example also illustrates the integration, within a single algorithm, of input from human motor activity, output to human auditory perception, and output to human somatosensory perception.

3.3.3 **Cost and mass-producibility** The KSFT system uses the same off-the-shelf personal computer and off-the-shelf electronic signals interface as the CT system (see above). Also, it uses the same coil circuit as part of its custom transducer electronics. This circuit here controls a different electromagnet, however, while input is now obtained via an optical mouse displacement sensor. This does not raise costs, since the
electromagnet is made in the same way as the one in the CT system; while the optical mouse hardware costs only € 40 (in 2014; for other details, see Section 2.3.4.1). Therefore, the hardware components of the KSFT system are mass-producible, at a cost (excluding the host laptop computer) again below € 1300.

3.3.4 Research goals attained in the resulting system  In the preceding subsections of Section 3.3, we have presented the KSFT system for computed fingertip touch. How, in summary, have the chapter goals identified in Section 1.6.9 been achieved in this system?

```plaintext
\begin{verbatim}
\texttt{t = Tactile10.new;
  \{
    a =
      SynthDef \{ "example",
          \{
            var cycleWidth_mm = 10,
            xPosRamp = \{ln.ar (t.xPos_mm_bus) / cycleWidth_mm \} % 1,
            yScalingFactor = LinLin.ar
              \{ln.ar (t.yPos_mm_bus),
               50, 90, 0, 1
             \};
          \}
        Out.ar // audio left and right
          \{[10,11],
            SinOsc.ar
              \{freq: LinExp.ar \{xPosRamp, 0, 1, 20, 8000\},
               mul: LinExp.ar \{yScalingFactor, 0, 1, 1e-02, 5e-04\}
             \};
        \},
    Out.ar // kinetic friction
      \{t.kfriction_bus,
        LinLin.ar
          \{xPosRamp, 0, 1,
            0.14, LinLin.ar \{yScalingFactor, 0, 1, 1.40, 0.14\}
          \};
      \},
    \}.play \{t.generalSynthesis_group\};
  \}.value;
\}
\end{verbatim}
```

**Figure 3.6** The KSFT system: code example. Highlighted in blue: regular audio output. Highlighted in green, from top to bottom: x displacement input in mm, y displacement input in mm, and kinetic friction output in N.
The first goal was to algorithmically represent transducer state using physical units. In the KSFT system, this is done using two displacement inputs in mm, a friction output in N, and a known latency in ms inbetween (see Sections 3.3.1.1 to 3.3.1.3). The programming interface for writing algorithms that use this I/O has been discussed in Section 3.3.2.

The second goal was to integrate computed sound. In the KSFT system, this has been done through use of the SuperCollider programming language (see Section 3.3.1.4). The code example given in Section 3.3.2 illustrated the resulting, complete integration.

The third goal was to support real-time instrumental control of musical sound. In the KSFT system, the latency between input from motor activity and output to auditory perception is only small enough to achieve this goal for slowly-made changes to heard musical sound (see Section 3.3.1.5).

The fourth and final goal was to realize a powerful, yet cheaply mass-producible system. Here, we understand the relative powerfulness of computed fingertip touch implementations in the same way as already discussed in Section 3.2.4. The KSFT system, then, can be regarded as powerful because, for fingertip movement at lower speeds and accelerations, its displacement input and friction output can cover the spatial range of surface roughness perception.

More precisely, in Section 2.3.4.2, we discussed how aspects of surface roughness perception are induced by details separated by 0.125 mm or more, and we also discussed how the obtained displacement input resolution of 0.02 mm seemed sufficient to support this. Now, when computing friction output to induce aspects of surface roughness, due to the average I/O latency of 20.5 ms, there will be a difference between the displacement speed on which computation is based, and the actual displacement speed during output. This error will be smaller, however, during fingertip movements with lower accelerations.

Also, as the shortest duration for perceptually effective features in friction output was found to be between 10 ms and 1 ms, the KSFT system can render apparent details of size 0.125 mm and larger as long as the absolute fingertip displacement speed stays below 12.5-125 mm/s. (In addition to the positional displacement inputs, the KSFT system was extended with displacement speed inputs, derived from the same sensor data, and yielding ranges from -334 mm/s to +334 mm/s, with a 2.6 mm/s resolution.)

Finally, we again understand a system for computed touch to be cheaply mass-producible, if large-scale production is possible at a cost comparable to that of common, widely used devices for personal computing. As discussed in Section 3.3.3, the KSFT system, excluding the host personal computer, is mass-producible at a unit cost below that of a mid-range laptop computer.