SONOPHENOLOGY : A TANGIBLE INTERFACE FOR SONIFICATION OF GEO-SPATIAL PHENOLOGICAL DATA AT MULTIPLE TIME-SCALES

Steven R. Ness, Paul Reimer, Norman Krell,
Gabrielle Odowichuck, W. Andrew Schloss and George Tzanetakis

University of Victoria
Department of Computer Science and School of Music
Victoria, BC, Canada.

ABSTRACT

Phenology is the study of periodic biological processes, such as when plants flower and birds arrive in the spring. In this paper we sonify phenology data and control the sonification process through a tangible interface consisting of a physical paper map and tracking of fiducial markers. The designed interface enables one or more users to concurrently specify point and range queries in both time and space and receive immediate sonic feedback. This system can be used to study and explore the effects of climate change, both as tool to be used by scientists, and as a way to educate members of the general public.

1. INTRODUCTION

The study of the yearly timing of biological processes is called phenology. Examples of this include when a particular species of tree first flowers in the year, when birds return from their migrations, or when frogs first emerge after winter. It comes from the Greek words for “to show or appear” (phaino) and “reasoning, or rational thought” (logos). It is an ancient field of study and people have recorded this type of information since the dawn of time. For example farmers have kept records about the emergence of their crops from year to year in order to help them determine the optimal time to plant crops in a specific geographic location.

In just the last few years, internet enabled collaborative websites have transformed the collection of phenology data from a discipline where the individual scientist or farmer records their data onto paper for primarily their own research or use, into one where large numbers of amateurs from the general public can all collect and enter their own phenological observations. Sites such as the National Phenology Network [1] and Nature’s Calendar [2] allow citizen scientists to record their own observations about when certain natural phenomenon happen. This type of approach is commonly referred to as Crowdsourcing.

Tangible interfaces are a new metaphor in Human-Computer interactions, where instead of having the user interact with only the screen and keyboard, the person interacts with physical objects in the real world. These types of interfaces can involve cameras, sensors, motors, actuators and displays, and merge the real and virtual worlds into a single unified user interface.

In this paper, we propose to sonify phenological data and let people explore these datasets using a tangible interface. Our proposed system could be used with both historical phenological data and also with the large quantities of crowdsourced phenological data that is just now becoming available. There are several aspects of phenology data that make it a particularly interesting candidate for control through a tangible interface and sonification. Ideally a system for exploring phenology data should allow the specification of both spatial and time range queries in addition to simple point queries i.e render the data from Tokyo and Osaka between 1985-1990. We design a tangible interface based on tracking of fiducial markers that can be used for specification of point and range queries in time and space over a printed map. Of particular interest is the relative timing of different events such as flowering happens earlier in the South than the North. Synchronicity and relatively timing are clearly conveyed in our sonification. We are particularly interested in installation and public outreach environments therefore the sonification has also been designed to be aesthetically pleasing and not intrusive.

2. RELATED WORK

In “The Climate Symphony”, [1] the author presents a sonification of 200,000 years of ice core data in an artistic presentation that is a combination of sonification and story-based narrative structure. Eight sets of time series data of the relative concentrations of a number of ions in this ice core were examined, and using Principal Component Analysis, these time series were reduced to three sets of time series data. These time series data were sonified with simple sine waves which were then amplitude modulated by the amount of ice sheets coverage. Interesting contributions of this paper include the idea that because of the variety of different cycles in global temperatures that are driven by climate forcing from the sun (on time scales of 400,000, 100,000, 40,000 and 22,000 years) there are natural periodicities to this data. By using the natural ability of humans to hear periodic structure in audio signals, this paper demonstrates that this type of data is amenable to sonification. Another important contribution of this paper is that it attempts to create a system that will engage members of the general public by providing an interesting and pleasant way to explore climate data.

In “Broadcasting auditory weather reports - a pilot project”, [2] a sonification system is described that generates a sonified summary of a days worth of weather data which is then broadcasted on a local radio station. The data that is sonified includes time markers, wind, rainfall, temperature, cloudiness, humidity as well as discrete events such as thunder, hail and fog. They then sonify a 24 hour period in a 12 second audio clip, and comment on the different mappings of weather data to sound that they tried. One interesting contribution of this paper was that they found it useful to explore the emotional content of music, and that the authors tried

---

[1] http://usanpn.org

[2] http://www.naturescalendar.org.uk/

to map pleasant weather events (like bright sunshine) to musical phrases that evoked pleasant emotions, and less pleasant weather conditions (such as rain) to more melancholy musical phrases.

Another related paper is “Sonification of Daily Weather Records” [3], in which the authors describe a system that sonifies the weather data from Lincoln, Nebraska. In this paper, the authors choose three different parameters to sonify, temperature, rainfall and snowfall. For the temperature, they take daily high and low temperature measurements and convert these to MIDI notes. Because of the sizable difference between the high and low notes, this produces a sonification with two independent melodic lines, which humans are able to independently track as separate streams, as previous research by Bregman has shown [4]. They also propose mappings for rainfall and snowfall, for these the authors use one, two and three note sequences to encode different amounts of rainfall and snowfall, for example, for rainfall events less than 0.05 inches, only a single note is sounded, and for rainfall events over 0.5 inches, a sequence of three consecutive notes are played. They chose this mapping in order to follow the metaphor that light rain makes only light plinks and that heavier rain “comes down harder”.

In “Atmospherics/Weather works: A multi-channel storm sonification project” [5], the authors describe a system for sonifying the meteorological data associated with weather storms using multi-channel audio. In this paper they present sonifications for two storms, one of which was a typical strong hurricane, and one was an extremely violent storm that was not predicted by existing meteorological models. They choose these two storms in order to test if their sonification of storms could help meteorologists develop insights into the differences between these storms. Besides the very interesting idea of using multi-channel audio to help users understand the data better, they also present ideas for a variety of different sonifications of weather patterns. They first identified a number of variables, including temperature, wind speed and humidity at a variety of elevations, and then did a simple mapping of this data to pitches. Another interesting idea that was employed in this paper was to correlate each geographical point on the map to a speaker and then to use loudness as an indication of wind speed. The authors report that this gave a dramatic spatialization effect to the data.

In the majority of existing system for sonifying scientific data the result of the sonification process is a monolithic audio signal and the amount of influence users have in the sonification process is minimal or non-existent. In contrast in our system we have tried to make the sonification process an interactive, exploratory experience. Our design has been informed by several different research topics: phenology, crowdsourcing, tangible interfaces, and sonification. In the following section we describe these different topics and show how they relate to our work. The resulting system which we call Sonophenology integrates these different influences in a coherent whole.

3. BACKGROUND AND MOTIVATION

3.1. Phenology

Phenology is the study of the timing of biological processes as they occur during various times of the year. The timing of biological processes are intimately linked to the environment in which the organisms exist, and one of the most important determiners of the timing of seasonal changes is the average local temperature. For example, during a warm year, cherry blossoms will flower earlier than they would during a year with a colder spring.

Recently, phenological data has been used in a number of research projects in climate change [6, 7, 8, 9]. In these studies, a general conclusion has been reached that changes in local and global temperature affect the timings of phenological processes, and that these processes are exquisitely precise measures of climate change. Currently these results are typically compared using using either statistical measures, such as the ANOVA (Analysis of Variance) tests such as in Doi [10] or using visual representations of this data such as graphs that show histograms of the timing of various events across years.

Data about winter temperatures have been recorded for the last 2000 years in China [11], and this data has been used to study climate variations. Another set of phenological data that has been used to study climate change is that of Burgundy grapes in France [12]. In this study, spring and summer temperatures from 1370 to 2003 were studied, and using the data from the ripening of this species of grape, it was possible to look at variations in temperature over this time span. These types of studies show that phenology data can be used as a source of proxy data for studying the climate. Karl Linnaeus, the founder of modern taxonomy, studied phenology extensively, and by making observations of the flowering of 18 different plant species across Sweden. In his research, he came to the conclusion that flowering plants are exquisitely sensitive weather instruments.

3.2. Crowdsourcing

Crowdsourcing is a relatively new phenomenon that has been enabled by the pervasive spread of the internet in society, and allows members of the general public to help scientists collect or analyze data. It is a new type of collaboration where non-specialists help expert scientists [13] and has been used to great advantage in a number of research programs [14] [15] [16]. Hong [17] presents results that show that a group of problem solvers with a diverse background can outperform smaller groups of experts.

Whereas it used to be the case that obtaining phenological datasets used to be a difficult and time consuming process, the advent of these websites will mean that there will soon be huge archives of phenological data. One of these sites that has already started to distribute data is the Nature Watch [3] website in Canada. This website has subprojects including IceWatch, PlantWatch, FrogWatch and WormWatch that monitor the timing of various physical and biological processes, including when ice is present, when plants emerge and bloom and when worms and frogs emerge from hibernation.

With the advent of these new crowdsourced sites for the collection of phenological data, the concept of phenology is becoming more well known in the general community. These websites have thousands of observers located in many geographical regions, and with this data becoming available, it can be anticipated that these citizen scientists will want to observe the results of their observations. Currently, results are usually presented in the form of a map with an associated timeline which allows the user to go back and forth in time to observe which plants are flowering at which places over time.

---

[3] http://www.naturewatch.ca

3.3. Tangible Interfaces

Tangible computing interfaces using tokens detected by computer vision techniques, such as the reacTable proposed by Kaltenbrunner, Jorda, and Geiger [18] have been tailored specifically for designing multimedia processing algorithms. The shape, translation, and rotation of tokens placed on a planar desktop surface controls some aspect of a multimedia processing pipeline. Early versions of these interfaces had an audio focus, to complement the visual process of designing an audio processing interface (e.g. an musical instrument). Tokens designed specifically for detection, classification, and spatial location/orientation are known as fiducial markers.

Fiducal marker detectors and trackers operate by identifying fiducials in a video frame, based on information that is known a-priori. Several visual properties can serve to identify a fiducial marker, (e.g. colour, geometry); several popular, state-of-the-art detectors use fiducials designed and identified by the topology of a hierarchy of shapes contained within the fiducial design, as described by Costanza and Robinson in [19].

Costanza, Shelley and Robinson[20] describe the application of this approach to detecting fiducial markers via the use of a region adjacency graph (RAG) to encode a two-level topology (e.g. black and white) of binary shapes into a tree structure representing that shape. Several constraints are imposed on marker designs by this choice of detector; markers must consist of white shapes wholly surrounded by black shapes, which in turn may enclose another level of black shapes. Detectors work on a binary-thresholded version of the input image, which allows some variation in the detected colour (e.g. off-white, near-black). A region adjacency graph can be generated for any number of levels, but in practice the number of levels is limited to three, denoted in [20] as root, branches and leaves.

Bencina et al. improve on the topological fiducial detector in [21], where the centroid of clusters of shapes contained in a lower level of the topology are used to rapidly reject candidate fiducial matches that do not conform to the structure of expected fiducials, and use this centroid information to discriminate between different fiducials.

Using a fiducial detector based on marker topology presents a tradeoff between marker complexity (and hence increasing size of the marker at the same level of resolution), and number of possible markers represented by different topologies of the same size.

Tangible interfaces based on positioning multiple fiducial markers placed on a multitouch table or desktop surface have many advantages over a conventional interface using a keyboard a mouse. These interfaces are a pure direct-manipulation modality: the user can intuitively see the structure they have created. Physical controls for parameters, visual representations of those parameters, and visualizations of the output produced by each processing unit, are located spatially nearby the fiducial token. The display plane and the control/interface plane are often aligned, preventing confusion common from a mouse/screen arrangement. Affordances are offered in multiple dimensions, for each fiducial marker detected (i.e. marker id, position, and rotation). This implies a simple marker printed on paper can yield more information than a dedicated, wired, peripheral such as a computer mouse. Indeed the costs of fiducial tracking hardware are little more than the cost of a conventional webcam and a printer for producing fiducial markers.

Each marker can be positioned by a separate person, and so marker-based interfaces lead easily to collaborative interfaces, since multiple people can use the same desktop surface with a separate collection of markers, or become more productive in assembling a single algorithm using multiple simultaneous operators.

In addition to using fiducial markers as physical controls independent from other markers, commonly a system of rules is designed to relate multiple fiducial markers present on the same desktop. Possible interactions include varying parameters of one or more markers, varying processing steps of one or more markers, or establishing an application specific chain of markers which interact in a pre-determined way.

We extend the concept of a tangible, fiducial marker-based interface used to create an aesthetically pleasing, and usable environment for exploring phenological data.

3.4. Sonification

Sonification can be described as the use of audio to convey information. In other words, scientific data is represented not as a visualization, like a graph, but instead as a collection of sounds that are played at different times.

The manner in which a given set of data is mapped to audio is a challenging problem, there are an infinite number of ways to transform data into a sonification[22]. Many aspects of any sound can be modified: we can perceive changes in amplitude, pitch, timbre, directional, and temporal information. Any of these auditory aspects, or audio parameters, can be modified by a data set. The best choice when selecting audio varies, depending on the content of a given set of data. The direction, or polarity, of the datasets that are being compared can also affect the perception of a sonification. For example, temperature is often described aurally as a tone with increasing pitch [23]. The scale of the relationship between a one-dimensional data set and the audio parameter modified by that data must also be considered. If we consider the temperature to pitch example, we must consider how quickly will the pitch increase, and whether the relationship will be linear or non-linear [24], that is to say, one wants to preserve the ratios, not the differences in frequency. The aesthetics of sonification are also an important consideration. The goal is to create a collection of sounds that represents a dataset accurately, and is also pleasing to listen to.

4. SYSTEM DESCRIPTION

4.1. Overview

Our system consists of a number of separate sub-components that interact together to provide a tangible interface for the exploration of geo-spatial phenological data. The overall organization of this system can be seen in Figure 1.

The phenological data sources that we obtained for this paper are quite diverse, and contain various types of information that could be used for sonification. In this application, we constrained our analysis to include only the species name, the latitude and longitude of the observation and the date when this observation was taken. Other data that we are not using for this paper includes the type of observation, for example, was the observation of the first bloom of the lilacs or when they were in full bloom. Many of the observations also include comments from the observers. These additional sources of data could be used in the future to enhance the audilization and visualization in our interface. We first sanitize

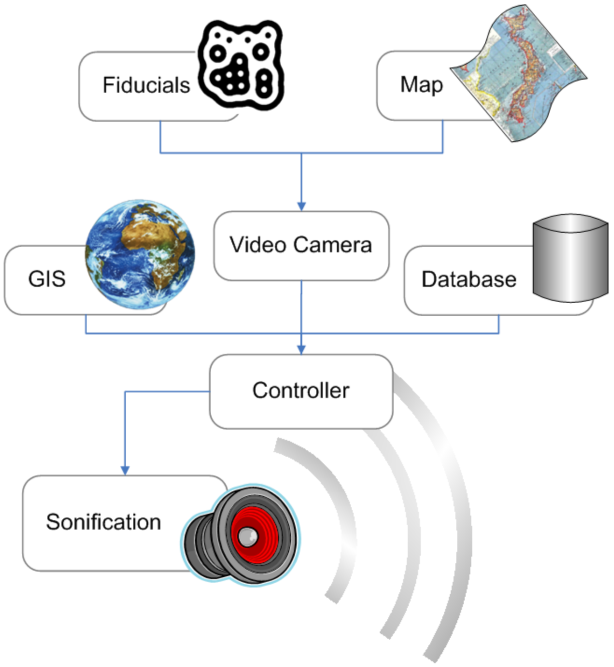

Figure 1: A flowchart of the system organization of our system. This system has at its core a Controller module that communicates with the phenology and GIS databases as well as the video camera and sonification engine. It generates sonifications by tracking the positions of fiducials on a printed paper map.

these data sources and read them into our GIS-enabled database system.

The second section of our system is the fiducial tracking interface. This uses a consumer grade webcam and tracks pre-printed fiducial markers on a surface. We also use fiducial markers to determine the position and orientation of the physical map underneath the fiducial markers. We then create a mapping from the set of coordinates of the fiducial markers to the physical latitude and longitude on the map. When the user places fiducial markers on the map, this system then takes the latitude and longitude of these points and queries the database to obtain corresponding phenological data points.

The final step in this system then involves taking these phenological data points, which include latitude, longitude, species and observation date, and sonifying them.

4.2. Phenology - Japan lilac

For this project, we are concentrating first on a set of observations of the flowering of the common purple lilac *Syringa vulgaris* in Japan [25]. Observations on the flowering of this species were collected from 1996 until 2009. Because of the large difference in latitudes between the south and north of Japan, flowers bloom earlier in regions in the south of Japan before they do in the north of Japan. These types of geographical differences are one source in the variation of flowering times. Another difference that may be possible to observe is the effects of climate change on the flowering times of these lilacs, however to truly see effects of climate change, one must of course examine temperature records over longer time spans, on time spans of centuries to millenia. If average temperatures increase over a period of years, one would expect that the phenological processes that respond to temperature would tend to move to earlier times in the year.

4.3. Tangible interface

Figure 2: Shown above is a picture of the fiducial tracking interface. Above the computer monitor is a small consumer grade video camera, which is pointed downwards in order to view the fiducial markers which are placed on a printed paper map.

While it would be possible to develop a simple desktop or web-based interface to explore a sonification of this data, a much more intuitive and engaging interface could be a tangible interface, where users interact with a physical interface. We have chosen a fiducial based tag tracking system previously used in the reacTable [18]. A picture of this system is shown in Figure 2.

This interface is inexpensive and easy to deploy, requiring only a consumer-grade webcam, physical printed map and printed fiducial tags, and could be easily deployed within a classroom setting. With such a system in a classroom, a teacher could teach students not just about phenology, climate change and maps, but also about new systems for physical interaction with computers. By moving markers across the map, the students experience a direct correlation with the location of the marker on the map and the associated phenological data.

In order to generate the query of the GIS database that contains the phenology data, we use two different user-interface metaphors. The first, simple method, is to simply use the center of the fiducial as the latitude/longitude search point and to return all data points

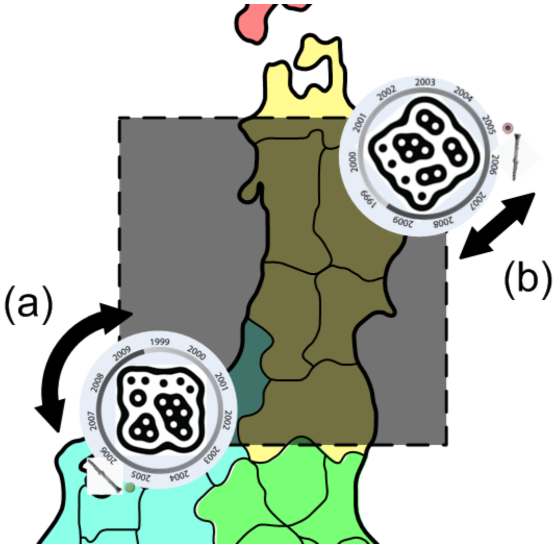

Figure 3: (a) Rotating the fiducials will change the sonification range. (b) Translating a pair of fiducials will sonify all data points found within the enclosed area.

that lie underneath that fiducial. A more complex setup that we have also implemented allows users to select a region of the map and a time range for each region. In this scheme, regions are created by placing two fiducials on the map. The first fiducial specifies the top left corner of a bounding box and the second fiducial specifies the bottom right corner. To change the time range that is sonified, the system calculates the relative rotation angle between the two fiducials and maps this to a value of years. This setup is demonstrated in Figure 3.

4.4. Sonifications

There are a number of advantages to sonifying these phenological data over using statistical tools and visual graphs. One advantage is that by using different timbres to represent the different sections of the map that we are sonifying, we take advantage of the fact that humans can distinguish different melodic streams that are rendered in parallel by different timbres. This could potentially allow a user to follow many different lines of data at once. This technique becomes even more powerful because of the distributed geographical and temporal nature of the phenological data, where flowers in the south bloom earlier than flowers in the north. These different melodic lines start and swell at different times, and the combination of different timbres with different start times of these timbres make it even simpler for users to follow the progression of phenological events.

Our primary sonification metaphor is that of a step sequencer, which uses a fixed two-dimensional grid consisting of quantized steps, with the horizontal axis representing time and different steps on the vertical axis being different instruments, or different pitches of one instrument. In our system, the vertical, or pitch axis, corresponds to different years, and the horizontal, or time axis, corresponds to the timing of the phenological event in days since the start of the year. This system allows us to easily hear and compare changes in the timings of different events over years by listening to the organization of pitches. If a phenological event occurs on the same date each year, one would hear a chord of all the notes at the same time. If on the other hand, the date of a phenological event becomes earlier each year, one would hear a descending arpeggio of notes.

The comparison of phenomena over various years is an essential part of this system, as one a primary motivation of this project is to provide a way for people to not just see but also hear and explore the effects of climate change. These different modalities of experience might prove effective in the education of people about phenology and climate change.

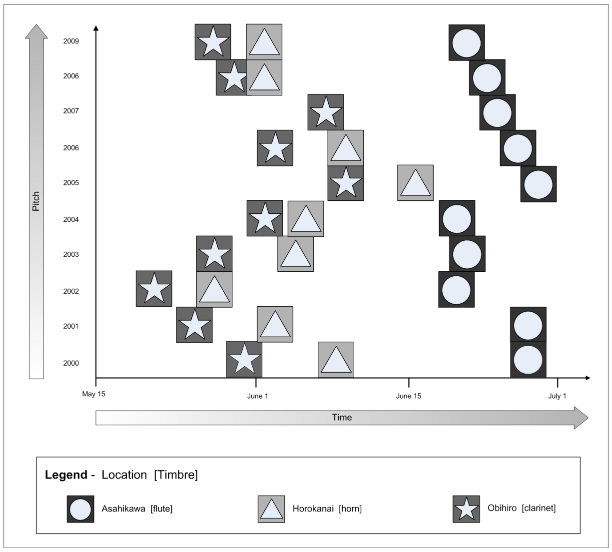

Figure 4: A graphical representation of 10 years of flowering data for the common lilac in three locations in Japan. The three different locations are depicted by different shapes, a circle, a triangle and a star. From this diagram, one can see that there are certain years (2002-2004) in which flowering occurred earlier than in other years.

One mapping that we have found to be useful is a step sequencer. In our system, one axis of the sequencer has pitches that correspond to different years, where earlier years have lower pitches, and later years have higher pitches. On the other axis of the step sequencer we have the day of the year. We also then map each fiducial marker to a different musical instrument or timbre. With this mapping, if the flowers in a specific region all flowered at the same time, then one would hear the notes from all the years sounding at once. On the other hand, if the flowering dates occur at later times each year, one would hear an arpeggio of notes with increasing pitches. A graphical view of three observation locations over a time period of 10 years is shown in Figure 4.

Another mapping that we are exploring is to instead represent each phenological observation as a distinct sonic event. This type of sonification produces a radically different soundscape which is more textural and ambient. One can imagine what this sonification sounds like by thinking of the timing of blooming of plants in the spring. One will often see one or two different plants of a species flower, then as time goes on more plants will flower in almost an exponential fashion until all the plants of the species have flowered. If one were to sonify each of these events as an impulse sound, then the sonification of this data would sound something like the popping of popcorn. What is interesting in this method is that it allows us to perceive the "stochastic" nature of the natural process, where each event is not significant unto itself, but the aggregate events outline a process that can be reflected in an auditory soundscape that reveals subtle differences in the rate of change of a physical system. Our ears are very sensitive to subtle differences in stochastic signals like colored (or filtered) noise.

When converting data into audio, there are a number of different mappings that can be used. The simplest would use a sinusoidal oscillator and would linearly map input data into the frequency of this oscillator. One disadvantage of this mapping is that in the human auditory system, the frequency to pitch ratio is not linear but rather is logarithmic. Because the human ear hears frequencies logarithmically, a logarithmic mapping of data to frequency would more accurately preserve the ratios of data points to each other. There are a potentially infinite number of mappings of data to pitch values, the one that we chose for this application was to map data values onto the equal tempered scale, as seen on the piano keyboard or MIDI note values. However, in our system, we anticipate that several values could occur at one point in time, and if we were to simply map data values to MIDI note values, it would be common to encounter dissonances in simultaneously played notes. To overcome this, one can use different scales or chords instead of the chromatic scale. In our system, we mapped the 10 different year values to the pentatonic scale. We are also developing mappings using chords, for example the notes of a C-sharp major 7th chord, or any other chord, could be used to map each year to a pitch component of the chord. Then the chronological order would determine the position of the year within the chord - in our example chronological order follows pitch height. One could use the same chord for all instruments with or without the same keynote, however, one could also use different chords for different instruments, which might have the advantage that it would further improve distinguishability for people by different melodic lines following the chords.

For most of our work in this paper we have used sampled sounds from the RWC dataset [26]. However, we have also implemented a synthetic instrument model in order to provide more and different sonification parameters. In doing this, we have implemented simple sine sources, plucked strings as well as more advanced synthetic models of physical instruments. The advantage to using these types of synthesized sounds is that it is possible to control different parameters of the sound, for example, the brightness of a clarinet sound, or attack speed of a trumpet, these parameters can then be mapped to the data that is being sonified. Using synthetic instrument models, one could also generate timbres that are intermediate between two instruments, for example, one could make a sound that was half-way between a clarinet and saxophone. This type of fine-grained control is difficult to implement using pre-generated samples. The main disadvantage to using synthetic instruments is that the models are often quite elaborate and are computationally expensive, which limits the amount of simultaneously playing instruments.

5. CONCLUSIONS

In this paper we have presented a system that takes geo-spatial phenology data and allows users to interact with it using a tangible interaction metaphor. The dataset of the flowering dates of Japanese lilacs was a useful dataset to explore with this system as it contained data points of flowering dates that occurred at different times and in different locations from the northernmost to the southernmost areas in Japan.

We have explored this dataset with our system. We have observed a number of interesting properties of the data and of the system. One interesting observation about this data is that in certain years the flowering of trees occurs earlier, and in some years they occur later. This is clearly heard in the sonification of this dataset because in these years, the note that is played for the different instruments is the same, and is repeated earlier in the cycle than those notes from other years. Another observation is that for the data points that occur earlier in later years, a descending arpeggio is indeed heard.

With the inclusion of the tangible interaction interface, this system is quite approachable for members of the general public, and in the few number of interactions that these individuals have had with our system, they find it both interesting and easy to use. We are currently considering doing user studies with this system, with the goal of building a system to help educate students and the public about climate change with an engaging interface.

In future work, we would like to develop a similar system to the one described in this paper but for mobile devices, such as the iPhone. This interface would allow people to interact with a computer generated map of a region, for example, a map of Japan and would allow people to explore the timing of various phenological events on their own personal mobile device. In conjunction with this, we are building a web-enabled version of this app using a combination of Flash and HTML5 technologies. The advantage of these web based and iPhone based applications is that they could have much wider penetration into the general community, at the cost of a more limited interaction metaphor.

This system can also be used for other phenology datasets, and as websites such as the National Phenology Network and Nature's Calendar start releasing their crowdsourced data, we anticipate that there will be a huge amount of phenological data that would be interesting to sonify. In addition, this system could also be used with other geo-spatial datasets, for example, one could develop an interface to allow scientists to sonify the amount and type of ground cover as determined by satellite images.

Although this system was developed as a tool to be used in a single location, in the future we would like to extend it to allow for remote collaboration between scientists. In this system, scientists in different cities could each have their own map, camera and fiducial markers. The fiducial markers would be mapped to unique instruments, so that for example, one scientist could use fiducial markers that correspond to different timbres. By exploiting the ability of humans to do auditory stream recognition, each scientist could choose to either focus on the sounds from the instruments that they are controlling or could focus on sounds that are being generated by a query from the fiducials of the other scientist. This type of multiple user interaction paradigm is often challenging when using visual interfaces because of problems of occlusion, reach and grasp, and could be more intuitive and easy to understand when using sonification instead.

We have made a website[4] that presents visualizations and sonifications of the data used in this paper, along with videos showing the system in action.

---

[4] http://sonophenology.sness.net

6. ACKNOWLEDGEMENTS

We would like to thank the National Phenology Website and Dr. S. Funakoshi for making the Japanese lilac dataset available to the scientific community.

7. REFERENCES

[1] M. Quinn, “Research set to music: The climate symphony and other sonifications of ice core, radar, dna, seismic and solar wind data.” Laboratory of Acoustics and Audio Signal Processing and the Telecommunications Software and Multimedia Laboratory, Helsinki University of Technology, 2001, pp. 56–61.

[2] T. Hermann, J. M. Drees, and H. Ritter, “Broadcasting auditory weather reports - a pilot project,” E. Brazil and B. Shinn-Cunningham, Eds., 2003, pp. 208–211.

[3] J. H. Flowers, L. E. Whitwer, D. C. Grafel, and C. A. Kotan, “Sonification of daily weather records: Issues of perception, attention and memory in design choices,” J. Hiipakka, N. Zacharov, and T. Takala, Eds., Espoo, Finland, 2001, pp. 222–226.

[4] A. S. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound*. MIT Press, Cambridge, Massachusetts, 1990.

[5] A. Polli, “Atmospherics/weather works: A multi-channel storm sonification project,” S. Barrass and P. Vickers, Eds., 2004.

[6] E. Post and N. C. Stenseth, “Climatic variability, plant phenology, and northern ungulates,” *Ecology*, vol. 80, no. 4, pp. 1322–1339, 1999.

[7] P. J, I. F., and P. Comas, “Changed plant and animal life cycles from 1952 to 2000 in the mediterranean region,” *Global Change Biology*, vol. 8, no. 6, pp. 531–544, 2002.

[8] G. Walther, E. Post, P. Convey, A. Menzel, C. Parmesan, T. Beebee, J. Fromentin, O. Hoegh-Guldberg, and F. Bairlein, “Ecological responses to recent climate change,” *Nature*, vol. 416, 2002.

[9] A. Menzel, T. H. Sparks, N. Estrella, and D. B. Roy, “Altered geographic and temporal variability in phenology in response to climate change,” *Global Ecology and Biogeography*, vol. 15, no. 5, pp. 498–504, 2006.

[10] H. Doi and I. Katano, “Phenological timings of leaf budburst with climate change in japan,” *Agricultural and Forest Meteorology*, vol. 148, no. 3, pp. 512 – 516, 2008.

[11] Q. Ge, J. Zheng, X. Fang, X. Zhang, and P. Zhang, “Winter half-year temperature reconstruction for the middle and lower reaches of the yellow river and yangtze river, china, during the past 2000 years.” *Holocene*, vol. 13, pp. 933–940, 2003.

[12] I. Chuine, P. Yiou, N. Viovy, B. Seguin, V. Daux, and E. Le Roy Ladurie, “Grape ripening as a past climate indicator,” *Nature*, 2004.

[13] J. Howe, *Crowdsourcing: Why the Power of the Crowd Is Driving the Future of Business*. Crown Business, 2008.

[14] J. Surowiecki, *The Wisdom of Crowds*. Anchor, 2005.

[15] D. C. Brabham, “Crowdsourcing as a model for problem solving: An introduction and cases,” *Convergence*, vol. 14, no. 1, pp. 75–90, 2008.

[16] J. Travis, “Science and commerce: Science by the masses,” *Science*, vol. 319, no. 5871, pp. 1750–1752, 2008.

[17] L. Hong and S. E. Page, “Groups of diverse problem solvers can outperform groups of high-ability problem solvers,” *Proceedings of the National Academy of Sciences*, vol. 101, no. 46, pp. 16 385–16 389, 2004.

[18] S. Jordà, G. Geiger, M. Alonso, and M. Kaltenbrunner, “The reactable: Exploring the synergy between live music performance and tabletop tangible interfaces,” in *Proceedings Intl. Conf. Tangible and Embedded Interaction [TEI]*, 2007.

[19] E. Costanza and J. Robinson, “A region adjacency tree approach to the detection and design of fiducials,” in *Video, Vision and Graphics*, 2003, pp. 63–69.

[20] E. Costanza, S. B. Shelley, and J. Robinson, “Introducing audio d-touch: A tangible user interface for music composition,” in *6th Intl. Conference on Digital Audio Effects*, no. DAFX-03, 2003.

[21] R. Bencina, M. Kaltenbrunner, and S. Jorda, “Improved topological fiducial tracking in the reactivision system,” in *Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR) - Workshops*, 2005.

[22] T. Fitch and G. Kramer, “Sonifying the body electric: Superiority of an auditory over a visual display in a complex, multi-variate system.” in *Proceedings of the First International Conference on Auditory Display*, 1992.

[23] B. N. Walker, “Consistency of magnitude estimations with conceptual data dimensions used for sonification,” *Applied Cognitive Psychology*, vol. 21, pp. 579–599, 2007.

[24] B. N. Walker, G. Kramer, and D. M. Lane, “Psychophysical scaling of sonification mappings,” P. R. Cook, Ed., International Community for Auditory Display. Atlanta, GA, USA: International Community for Auditory Display, 2000. [Online]. Available: Proceedings/2000/WalkerKramer2000.pdf

[25] S. Funakoshi and F. Kanda, “Phenological study of common purple lilac flowering as a study program for environmental education,” *Journal of Environmental Education*, vol. 3, pp. 77–81, 2000.

[26] M. Goto and T. Nishimura, “RWC music database: Music genre database and musical instrument sound database,” in *Proc. Int. Conf. on Music Information Retrieval (ISMIR)*, 2003.