

Figure 1. The interactive visualisation can be explored directly through touch. Data can be manipulated vertically and horizontally in a continuous space with torus topology mapped onto the sphere.

Mobile Phone Usage Cycles: A Torus Topology for Spherical Visualisation

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Abstract

In this paper we present a novel technique for visualising cyclical data on a spherical display. We developed a visualisation that represents axes such as weekly and hourly cycles with an interaction that is topologically toroidal but visually spherical. This is used to develop a natural, continuous interaction for exploring temporal patterns on a spherical display. We describe our implementation of this visualisation, explore a practical data set that captures longitudinal mobile phone usage [4], and discuss the advantages of spherical visualisation.

Author Keywords

Spherical Display; Interactive Data Visualisation; Mobile Context Data; Cyclical Data.

ACM Classification Keywords

H.5.0 General.

Introduction

Spherical displays provide unique opportunities to create interactive data visualisations. Data sets with cyclical characteristics, such as mobile phone usage data [5], are better suited to visualization where weekly and hourly patterns of behaviour can be visualised on a continuous surface. This paper explores a novel technique for visualising such data using a spherical display.

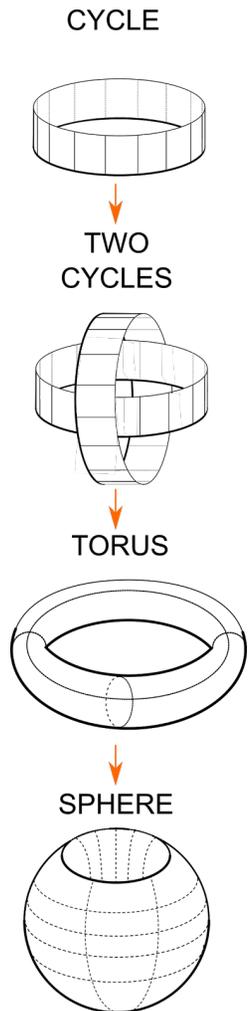


Figure 2. Two cyclical series can be represented as a torus, and transformed to a sphere by a smooth deformation.

The recent availability of interactive spherical displays as a commercial product [13] now makes it possible to explore new ways of visualising data on spheres. Spherical displays have been used in a variety of contexts, such as gaming [11], artistic installations [10], and collaborative interfaces [3]. However, research on spheres as *visualisation* devices is limited beyond simple globe-type geographical visualisations.

A programme of research is necessary to understand how data should be visualised on a sphere, what type of data can benefit from spherical visualisation, and what interaction techniques and metaphors can be most effectively used for data exploration and analysis. In this paper, we present a novel visualisation technique for cyclical data, which we demonstrate using a mobile phone usage data set. Our technique maps a torus topology to the sphere to support continuous interaction with the modular elements of the dataset.



Figure 3. Globe-based visualisations are a simple way to map data directly onto a spherical display.

Why Spheres?

Why use a spherical display for information visualisation? Spheres have a corner-less geometry

that makes them attractive for visualisation, and they enable new types of interaction and collaborative opportunities [2].

The content on a spherical display is borderless but finite, meaning that *continuous* content can be displayed both vertically and horizontally. The entire display is never completely visible from one perspective. While areas on the top may be visible to multiple users around the display, lower areas of the screen can only be seen from certain perspectives. This creates implicitly shared and private areas of the screen, allowing users to crowd around the display and interact collaboratively. Users can orientate their bodies towards each other and interact while maintaining eye contact and gesturing over the top of the display. Like King Arthur's round table, the display does not have an intrinsic *front* or *centre*, meaning that users can approach from any side and interact simultaneously. These affordances together make spherical displays unique, creating novel social dynamics around the display.

A simple direct mapping can be used for displaying geographical data at a planet-level scale, creating a modern interactive version of a traditional desktop globe. For example, the *GlobalFestival* application (shown in Figure 3) visualised performers from around the world based on their home towns during an international music festival [9]. This approach, however, has drawbacks and does not fully exploit spherical visualisation. A globe cannot easily support zooming, since that would violate continuous geographical mapping onto a sphere. Such visualisations are dictated by geographic constraints, offering limited opportunities to improve the usability of

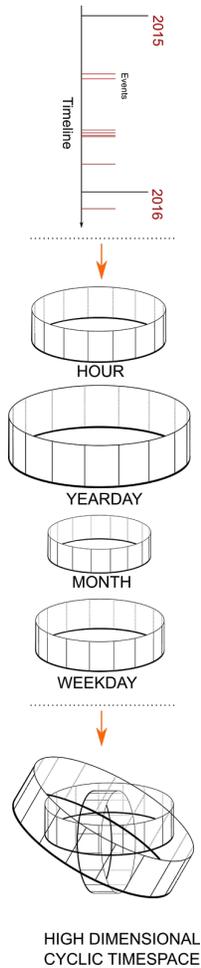


Figure 4. A timeline can be factored into pseudo-independent semantically-meaningful cycles to create a high-dimensional timespace.

the visualisation while maintaining a recognisable globe. However, there exist multiple applications of spherical visualisations *beyond* the globe metaphor that better exploit the affordances of the sphere.

Spherical Visualisation

In projection models with low-dimensions, spherical surfaces have a topology which conforms significantly better to the high dimensional original space than a flat 2D surface [4]. Self-organising maps (SOMs) have been used to layout spherical structures [6,12] because of the SOMs flexible projection layout. Previous work has indicated the theoretical advantage of spherical low-dimensional layouts, but lacked the physical hardware to build effective interactive visualisations.

Cyclical data

Besides the geometric benefits for projection, spheres are also a natural medium for representing cyclical data. Unlike a flat display, which has to either unravel a cycle into a flat strip, or waste space representing the cycle as a circle, spheres naturally support data that repeats in cycles, as shown in Figure 4. Such interactive spherical visualisations are now practical with the advent of commercial interactive spherical displays [13].

In this paper we show a novel mapping of two dimensions of cyclical data that can be used to draw insight from a dataset. These insights derive from an elegant, topology-preserving mapping of the data with touch interaction that supports direct-manipulation exploration.

Modular visualisation

Events occurring over time are often represented on a time line. While this is a simple and clear visualisation, human and environmental time has a rich internal structure. Human activity typically takes place in daily, weekly, and seasonal cycles. Representing time visually as a set of interlocking cycles can reveal stark patterns that are not apparent in a linear layout. Examples of such human rhythms range from commuting activity in the morning and evening, socialisation repeating on weekend evenings, annual holidays clustered around religious celebrations and school breaks, right down to the minute-level rush of activity surrounding the “top of the hour” as people hurry from one meeting, class or appointment to another.

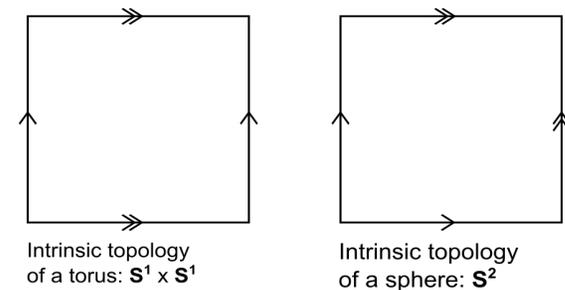


Figure 5. *Gluing diagrams* [7] showing that the intrinsic topology of a torus is incompatible with that of a sphere.

The natural way to represent such cycles is as a modular structure. For example, day of week is the day number modulo 7; the hour of the day is the hour number modulo 24, and so on. Slightly more sophistication is needed to get irregular month timings aligned.

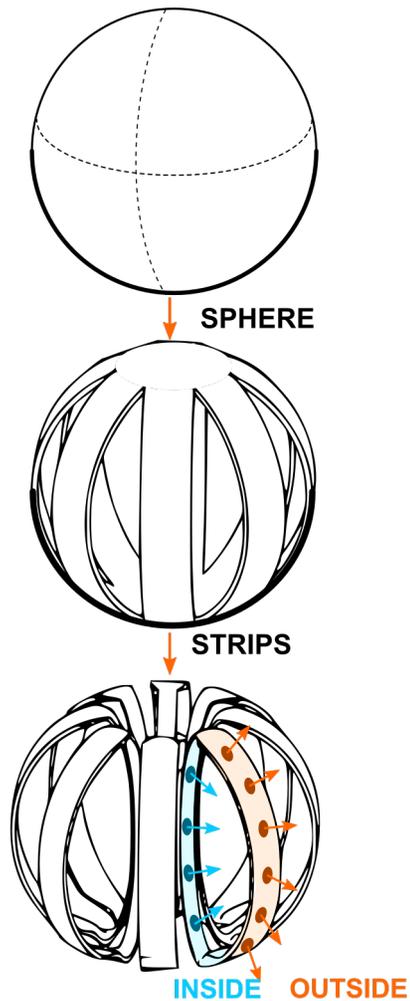


Figure 6. Transforming a sphere to a torus by splitting into strips which represent continuous bands with an inside and outside.

A linear time series can be represented in this form by first taking time units modulo the cycle of interest and then quantising to the natural divisions of that cycle (e.g. hourly divisions can be computed from base units of seconds as $\text{floor}(\text{seconds}/3600) \bmod 24$).

This transforms the straightforward, one dimensional, ever-increasing time t into a high-dimensional vector $\mathbf{c}=[c_0, c_1, c_2, \dots, c_n]$ for each cycle c_i , which captures the internal cyclic structure of activity. Projections and metrics can be defined to explore and analyse this enriched space. The geometry of cyclic space means that differences between times can be extended beyond simple elapsed time between events, $\Delta t=t_1-t_2$. This high dimensional timespace can *simultaneously* capture and represent similarities between days of the week, or hours of the day or seasons of the year: $\Delta t=f(\mathbf{c}_1, \mathbf{c}_2)$ for some metric $f(x, x')$. These concepts are described in the context of photo browsing in [8]

These transformations apply equally to other variables that have cyclical structure, but time is a dominant independent variable in many domains and has a singularly rich decomposition into independent cycles [1].

Torus topology on spherical surfaces

A challenge with this approach is to efficiently display these structures in an informative and aesthetically pleasing interactive visualisation. We used a commercially available interactive spherical display [13] to represent two cyclic dimensions simultaneously. To illustrate our approach, we visualised a dataset representing longitudinal behavioural patterns in smartphone usage [5].

Each cycle can be represented on a circle of a topology, as shown in Figure 5, where S_1 is divided into discrete sections. A pair of these dimensions therefore has topology $S_1 \times S_1$, which is topologically a torus (see Figure 5, left). This is quite distinct from the 3D spherical topology S_2 (see Figure 5, right).

We developed a technique using a continuous distortion to project from the toroidal topology to the spherical surface, making it easy to interactively manipulate, at the cost of some limited geometrical distortion. Our technique maps longitudinal touch motions to straightforward longitudinal rotations, but maps latitudinal touch motions to toroidal shifts, as if the space was pushed up through the poles and pulled out through the bottom, as shown in Figure 7.

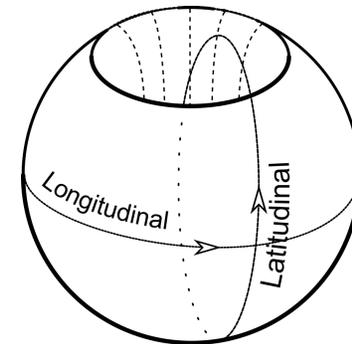


Figure 7. The torus-sphere rotation interaction model.

Visualising Smart Phone Usage

We developed a novel visualisation of behavioural patterns in smartphone usage to demonstrate visualising cyclical data on a spherical display (Figures 1 and 8).

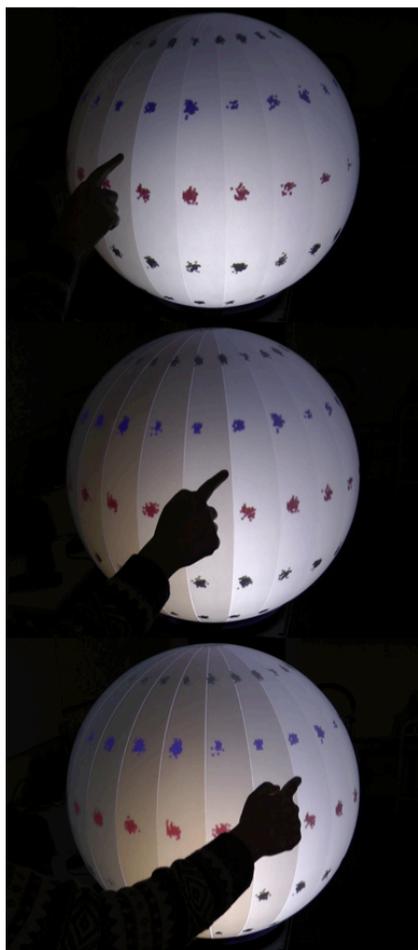


Figure 8. Latitudinal drags rotate the visualization around the polar axis.

Smartphone Usage Data

Our visualization uses data collected with the AWARE mobile phone context instrumentation framework [5]. This is a time series of user activity on a mobile device, spanning several months from multiple users. The visualization focuses on users' foreground application activity, although the data set also includes additional information such as phone and message activity, charging activity, and battery level.

Our visualization maps the day of the week to the latitudinal cycle and the hour of the day to the longitudinal cycle. The visualization is fully touch interactive, supporting dynamic manipulation using the torus topology described in the previous section.

Implementation

We implemented the transformation as a warping of points on a sphere in Cartesian space (x,y,z) . Data points are projected into these coordinates by transforming each data point to spherical coordinates latitude, longitude $[\phi, \theta]$ and then transforming to Cartesian space. By applying a different rotation to each (infinitely-thin) longitude "strip" θ we can approximate the toroidal topology as precisely as desired.

We developed a GLSL shader to implement the transformation efficiently. This lets us run the visualization at interactive rates with 10^4 data points. To minimize geometric distortions, we attached a common centre vector to all the vertices of connected geometric primitives. This centre vector is used to determine the torus rotation to be applied; i.e. which "strip" the primitive lies on, as shown in Figure 6. This means that circles stay circular everywhere on the

sphere, and likewise for other shapes, with no local geometric distortion.

All of the geometry is duplicated with the centre vectors flipped, to represent the points "inside" the sphere. These points are ready to be rotated into place as the sphere is manipulated.

This results into each longitude strip being a continuous band with two copies of the geometry on it. Exactly half of this (the part on the "outside") is visible at any given time. This visual outcome is an apparently seamless movement. After the shader applies the toroid transformation, the resulting vertices are tested to determine if they are on the sphere's exterior, and if so are transformed to the display's native azimuthal equidistant projection to be rendered on the device.

Cueing and Animation

The edgeless, unoriented nature of the sphere makes cues essential to understanding the structure of the space. Our visualization uses a number of cues to aid interpretation of the data during manipulation. Hours of the day are shaded as wedges on the sphere to reflect daylight colours, with deep blue during hours of darkness, pale blue during sunrise, warm yellow during daylight, and orange during sunset. Saturdays, Sundays, and Wednesdays are given special colours, red, blue, grey, respectively, to mark out the weekly structure. We found such directional cues to be critical because of the free orientation of the space.

The visualization also includes an animated mode, where each cluster of data points "swarms" in place. This makes it easier to see the density of clusters by reducing overlap.

Discussion

Spherical visualisation offers exciting opportunities to explore and visualise datasets in a way that flat 2D representations do not capture. Our initial work demonstrates that cyclical data is especially suited to this technique, allowing for continuous visualisation that is not practical using a flat display. Our technique maps a torus topology to the sphere to visualise cyclical data using two modular components in a mobile phone usage data set [5], i.e. day of week (latitude) and hour of day (longitude).

One of the biggest advantages of spherical visualisation is that data can be represented continuously. However, this feature can also make it difficult to situate local views in context or understand the directionality of the data, for example, if data should be “read” top to bottom or vice versa. In our visualisation, we used colour cues to mark landmarks in the data, but more research is needed to identify to best techniques for providing such visual cues and determining user preferences for how and in which direction data should be mapped to the sphere.

The interactive visualisation allows users to manipulate the data through direct touch, but interaction metaphors on spheres are still relatively unexplored. Although some gestures have been explored for spherical displays [2], these have been limited and don’t support fine manipulations. When interacting with discrete elements (data points) in continuous space (modular visualisation), new interaction techniques and metaphors will be required to fully exploit interactivity on the sphere.

Another interesting implication is the collaborative nature of the display and the unique social dynamics that can develop around the display. Our current prototype does not specifically support collaboration, but the sphere is ideally suited to support this. Bolton et al. demonstrated that software techniques could aid collaboration, but that users also used the physical space around the sphere to collaborate [3].

Conclusions

This paper presents a novel technique for visualising data on a spherical display. A novel topological transform from torus to sphere was used to engineer a compelling simultaneous visualisation of multiple cyclical elements of a time series which supports direct touch manipulations. Our initial explorations with the mobile phone activity dataset suggest that spherical representations are a very promising approach to visualisations that have been underserved by traditional flat displays.

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Code resources that implement this technique are available at:

<https://github.com/johnhw/pyuffersphere>

References

- [1] Aigner, W., Miksch, S., Schumann, H., and Tominski, C. *Visualization of Time-Oriented Data*. 2011.

- [2] Benko, H., Wilson, A., and Balakrishnan, R. Sphere: multi-touch interactions on a spherical display. *Proceeding UIST '08 Proceedings of the 21st annual ACM symposium on User interface software and technology*, (2008), 77–86.
- [3] Bolton, J., Kim, K., and Vertegaal, R. A comparison of competitive and cooperative task performance using spherical and flat displays. *Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work - CSCW '12*, (2012), 529.
- [4] Brennan, D. and Hulle, M. Van. Comparison of Flat SOM with Spherical SOM: A Case Study. *The Self-Organizing Maps and the Developments - From Medicine and Biology to the Sociological Field*, (2007).
- [5] Ferreira, D., Kostakos, V., and Dey, A.K. AWARE: Mobile Context Instrumentation Framework. *Frontiers in ICT 2*, April (2015), 1–9.
- [6] Nishio, H., Altaf-Ul-Amin, M., Kurokawa, K., and Kanaya, S. Spherical SOM and arrangement of neurons using helix on sphere. *IPSJ Digital Courier 2*, Tom 14 (2006), 133–137.
- [7] Weeks, J.R. and Francis, G.K. *A Topological Picturebook*. 1988.
- [8] Williamson, J. and Brown, L. Flutter: directed random browsing of photo collections with a tangible interface. *Scenario*, (2008), 147–155.
- [9] Williamson, J.R., Sundén, D., and Bradley, J. GlobalFestival: Evaluating Real World Interaction on a Spherical Display. *Proceedings of the Joint International Conference on Pervasive and Ubiquitous Computing and the International Symposium on Wearable Computers (Ubicomp/ISWC'15)*, (2015), 1251–1261.
- [10] Williamson, J.R. and Sundén, D. Enter the Circle - Blending Spherical Displays and Playful Embedded Interaction in Public Spaces. *Proceedings of the 4th International Symposium on Pervasive Displays (PerDis'15)*, ACM (2015), 195–200.
- [11] Williamson, J.R., Williamson, J., Sundén, D., and Bradley, J. Multi-Player Gaming on Spherical Displays. (2015), 355–358.
- [12] Wu, Y. and Takatsuka, M. Spherical self-organizing map using efficient indexed geodesic data structure. *Neural Networks 19*, (2006), 900–910.
- [13] Pufferfish Displays. <http://www.pufferfishdisplays.co.uk/>.