Energy Balance: A web-based Visualization of Energy for Automotive Engineering using X3DOM

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***Abstract*—Automotive systems can be very complex when using multiple forms of energy. To achieve better energy efficiency, engineers require specialized tools to cope with that complexity and to comprehend how energy is spread and consumed. This is especially essential to develop hybrid systems, which generate electricity by various available forms of energy. Therefore, highly specialized visualizations of multiple measured energies are needed. This paper examines several three-dimensional glyph-based visualization techniques for spatial multivariate data. Besides animated glyphs, two-dimensional visualization techniques for temporal data to allow detailed trend analysis are considered as well. Investigations revealed that Scaled Data-Driven Spheres are best suited for a detailed 3D exploration of measured data. To gain a better overview of the spatial data, Cumulative Glyphs are introduced. For trend analysis, Theme River and Stacked Area Graphs are used. All these visualization techniques are implemented as a web-based prototype without the need of additional web browser plugins using X3DOM and Data-Driven Documents.**

***Keywords*-scientific visualization; spatio-temporal multivariate; glyph based; trend analysis; web-based.**

I. INTRODUCTION

Scientific visualization is a growing field of research in computer graphics. The enormous amount of measured and calculated data has rapidly grown. To make fast decisions based on the data, scientists and engineers need to interpret valuable information efficiently. The complexity of this data constantly increases and therefore highly specialized and individual visualization methods are needed [1].

Especially automotive engineering encounters the need to develop more efficient energy saving systems to provide longer duration with a given amount of energy. Thus, automotive engineers require specialized tools that support them to achieve this goal. An increasing research field of automotive engineering are hybrid vehicles (e.g., combination of combustion engine and electric propulsion system). As electricity is used for propulsion, several forms of energy can be used to generate electricity [2] (e.g., heat, kinetic energy or sun light). A hybrid vehicle that uses multiple forms of energy can be a very complex system. Every single component that outputs or consumes energy must be considered to ensure highest efficiency. To cope with such complex systems, engineers need to be able to understand the global behavior of such hybrid systems.

In this paper, several multivariate visualization techniques (two- and three dimensional) are evaluated (see Section II). In addition to that, a prototypical implementation using X3DOM [3] and Data-Driven Documents (D^3) [4] technology is discussed (see Section III). This interactive prototype demonstrates two glyph-based three-dimensional (3D) visualization methods including Scaled Data-Driven Spheres (SDDS) and three different two-dimensional (2D) visualization methods called ThemeRiver [5], Stacked Area Graph and Stacked Cumulative Percent Plots [6] (see Section IV and V). The conclusion in Section VI complete this paper.

II. RELATED WORK

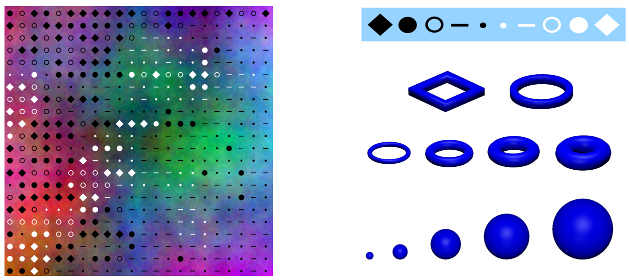
A. Data Visualization

There exist many visualization techniques for multivariate data like Geometric Projection, Pixel-Oriented Techniques and Hierarchical Display [1]. The given data model is not only a general multivariate data set, but it also has temporal and spatial components, which play an important role.

Temporal or so-called time-oriented data has become a separate research field. There are various visualization techniques for temporal data and different purposes (e.g., ThemeRiver, TimeWheel) [7]. Generally, they have in common the depiction of the change over time.

On the other side, previous research also found multiple visualization methods for spatial-multivariate data, which are mostly used for scientific visualizations. These techniques include surface based rendering, direct volume rendering and glyph based techniques [8]. A large field of application for visualization methods for spatial-multivariate data are medical data visualizations (e.g., data from Nuclear Magnetic Resonance (NMR)). In the next section several related visualization techniques are presented, which have been considered for visualizing various forms of energy for automotive engineering.

Quantitative Texton Sequences (QTonS) is a bivariate visualization technique. It maps one dimension to a spec-



(a) (b)

Figure 1. **(a)** QToS with both negative and positive values **(b)** from top to bottom: Example of a Quantitative Texton Sequence - Cornered and round supertorus - Supertorus of various thickness - Scaled Data-Driven Spheres of different size.

trum color sequence and the other to a QTonS sequence (see Figure 1(b)). These two corresponding dimensions are distributed over an 2D area [9]. Fundamentally, values are mapped to individual Textons. The higher the absolute value is, the bigger the Textons surface will be. To differentiate negative and positive values, black and white Textons are used. In this case, black Textons represent negative values (see Figure 1(a)).

Superquadrics are a category of geometrical shapes, which basically are derived from ellipsoids and quadrics. Their appearance can be changed by changing their parameters (e.g., roundness of corners, size, color, etc.). This property can be exploited to map values to the glyphs appearance resulting in a glyph-based visualization (as illustrated in Figure 1(b) and 1(b)). Thus, Superquadric Glyphs can be used to visualize up to four dimensions in addition to the glyphs position.

Scaled Data-Driven Spheres (SDDS) is another glyph based visualization technique, which extends the 2D Data-Driven Spots [10] to 3D. SDDS use spheres as glyphs and it implies the properties of superquadrics like color and size. In addition to that, they are easier to interpret due to their simple shape and viewing angle independence. A previous user based evaluation of superquadrics and SDDS revealed that SDDS result to a lower error rate in value estimation and relationship identification [11].

Theme River is a two-dimensional visualization technique designed for trend analysis over a serial dimension (e.g., time) [5], [12]. Theme River enables users to compare different identities, which occur parallel. Every identity is represented by a colored current within the river (see Figure 2(a)). The higher a value is, the wider the corresponding current will be. If a value changes along the serial dimension, the currents width will proportionally change to it. Hence, abrupt changes and long term trends can be recognized easily. If a value equals zero, the appropriate current will disappear until it changes its value again.

Stacked Area Graph represents serial values as areas. The x-axis represents a serial dimension and the y-axis

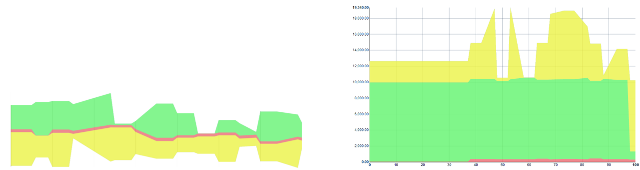


Figure 2. **(a)** Illustration of Theme River with three currents. The width of current represents the corresponding value. It is primarily used to identify trends. Thus, labels indicating the exact value are not essential. **(b)** Illustration of Stacked Area Graph with three elements. The height of stack element expresses the corresponding value.

represents the corresponding value. When values change over a serial dimension, the height of the corresponding area will change as well. If multiple values are depicted, areas are not overlapping. They are arranged as a stack. Thus, the total sum of all depicted values is represented by the total height of the stack (see Figure 2(a)).

Stacked Cumulative Percent Plot (SCPP) is another graphical method for visualizing trends [6]. In contrast to Theme Rivers and Stacked Area Graphs, SCPP depicts the percentage instead of the value as stacked areas. The total graph is always stacked up to 100%.

B. *Web Technology*

As these visualization techniques have to be implemented with the aid of current web technologies, X3DOM is used to render all 3D visualizations. Generally, X3DOM is a new approach to enable web browsers to render 3D content without the need of further plugins [3]. The current HTML5 standard defines X3D (derived from VRML97) to be used to provide 3D content, but it does not define how this 3D content has to be handled. For that, X3DOM has been approached to connect the web browsers *Document Object Model* (DOM) containing the X3D data, with the internal X3D runtime. The X3D runtime does all 3D tasks, which are needed to render the scene defined by the X3D data. Using X3DOM there is no need to struggle with low-level graphics interfaces like OpenGL provided by WebGL [13]. Due to its observer architecture, it also supports dynamic DOM changes, which effect an analogous update of the X3DOM runtime content. X3DOM has not been declared as a web standard, but like XML3D [14], it runs for it.

III. PRECONDITIONS

A. *Data model*

Problem-specific visualizations are tailored for specific data. Thus, it is important to know the underlying data structure. In our case, we have a spatio-temporal multivariate data. The data consists of the energy type, the 3D position where the data was collected, the data acquisition time and the measured (positive or negative) value itself.

The multivariate data has 6 dimensions:

- form of energy (one dimension)

- value (one dimension)
- time (one dimension)
- 3D position (three dimensions)

Each value sequence represents the recording of a single sensor (measuring point). All values are measured parallel and it can be assumed that all sensors have been synchronized. Hence, the n^{th} value of every value array represents the same time.

B. Visualization

The visualization must be capable to display five distinct forms of energy and an arbitrary number of sensors in an explorable way. These forms of energy should be easy to interpret, to distinguish and to compare. In addition, the trend over time must be easy to investigate to satisfy the requirements of automotive engineers. To achieve that, both 2D and 3D visualization techniques will be considered.

Summing up, an optimal visualization meets these requirements:

- displaying at least five distinct forms of energy measured by several hundred sensors
- easy exploration of data, especially considering spatial and temporal dimensions
- opportunities to compare measuring points and different forms of energy
- gives a global overview about the data
- opportunities for detailed trend analysis

IV. Examination

Basically, the human's perception capabilities are limited to a 3-dimensional spatial sense plus a perception of time. This results to a 4D world, in which we live in. This limitation also narrows the possibilities of beneficial visualization methods, while the perception of time can only be used via animations. Thus, a single image can not exploit the perception of time. Regarding this fact, properties of geometrical shapes (glyphs) (e.g., color, size, roundness, pattern and orientation) can be used to gain the feasibility to visualize even more dimensions. This is needed to display multi-dimensional data.

An investigation of existing techniques revealed that a combination of 2D- and 3D visualization techniques lead to a better global insight into the measuring data. Moreover, this allows the user to investigate the data from different points of view.

A. 3D visualization

If the data has a spatial component and it is important to know its location, it is common to use a visualization technique that retains this spatial information. The drawback of this decision is, that every visualized dimension consumes a single dimension in the visualization space. For our problem, all three dimensions of the spatial variable are used because the cognition of the energy's location is essential. Therefore, no spatial dimension for visualizing time is left. Three-dimensional visualizations also allow more freedom to explore the spatial data in a natural way.

QTonS are considered to be used as a render mode of the three-dimensional space to represent the two dimensions *value* and *form of energy*. While exploring the 3D-space, the view is updated by the QTonS technique to represent the amount of energy in the viewed region. The mapped colors represent the *form of energy* and the texons represent the *value* of the data (see Figure 1). The drawback of this approach is, that the location of the visualized energies is not clearly evident. The user can only perceive how much energy occurred in a specific direction calculated from the viewpoint. Therefore, it is not possible to investigate a single location. This results to an ineffective explorable visualization. Moreover, it is rather suitable for data sets of high spatial density. Such a high density might be reached by some measurements but this is not the common case. It is assumed that common measurements have up to several hundred measuring points distributed over the vehicle.

Torus-based Superquadric Glyphs can be used to encode up to four dimensions using only their shape [15]. A possible setup would map the *form of energy* to the glyphs color; contrasting colors should be chosen [16], [17]. The absolute energy value is mapped to its thickness. To indicate if a *value* is either positive or negative, the roundness of the superquadric is used. However, when glyphs are placed densely, it is difficult to differentiate the glyphs and to identify patterns [11].

Scaled Data-Driven Spheres can be described as a point-cloud with the energy value modifying the radius of the spheres. To be able to display negative energy values, different colors are used (dark color for negative, light color for positive value). As humans perception struggles to differentiate more than 12 color values [17], ten colors remain, which is enough to visualize five energy forms (leaving out black for captions and white for background).

To illustrate change of values over time, a key frame animation is used, which interpolates between the radius of the spheres and its color (if the sign changes).

Due to the ease of interpreting SDDS, their low error rate in value estimation and relationship identification, SDDS are the most suitable visualization technique to display detailed measuring data spatially.

For large amounts of data points it may not be feasible to display all data, but to partition the data set into regions instead. This approach makes it easier to keep track of behavior and dependencies. The Cumulative Glyph (CG) visualization can be used to display the energy emission in these regions. A single glyph consists of several discs with each disc representing one energy form in such a region. These discs are usually depicted using icons identifying those energy forms. The color of each of those discs

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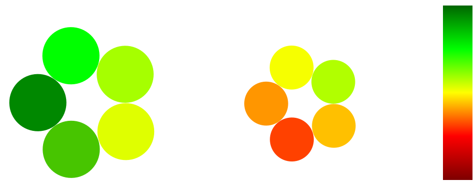

Figure 3. **(a)** Cumulative Glyph with only positive values **(b)** Cumulative Glyph with both negative and positive values **(c)** Color scale used for mapping energy values to colors

shows how much energy of one form is emitted (green) or consumed (red) in total in that region (see Figure 3).

B. 2D visualization

Due to Theme River's properties, it is suitable to depict the trend of measured values. While the serial dimension is the time component of a measurement, every sensor is represented by one current within the river. Currents that represent sensors measuring the same form of energy are of the same basic color and are placed side by side. As a result, these sensors together generate a wide current representing the total amount of one form of energy. Additionally, the total width of the river describes the total amount of energy. This allows users to compare trends of different forms of energies and various sensors at once. A drawback of Theme River is the difficulty of estimating values. Without any labels, users can hardly guess what value is represented by a given width. Moreover, Theme River works only with positive values. Thus, either absolute values should be used (where negative values are represented by darker colors) or two graphs, one for positive and the other one for negative values might be a solution. The latter solution should be preferred, because the former one treats positive and negative equally, which leads to a wrong representation of the total energy occurrence.

Stacked Area Graphs can also be used to examine the energies trend over time. Every measuring point is represented by an area. As implemented in Theme River, measuring points representing the same *form of energy* are placed next to each other. In addition, they are of the same base color to represent the overall occurrence of that specific *form of energy* as a cumulated area. This enables users to investigate the trend and to identify the entire amount of energy in an area (e.g., engine or front wheel). Negative values are represented by stacks below the x-axis. To navigate through time, controls for setting the displayed interval should be provided. Possibilities to set start time and end time independently allows users to *zoom* within the dimension of time.

Stacked Cumulative Percent Plots are very similar to Stacked Area Graphs. Due to the depiction of percentages instead of values, users can easily recognize which energy contributes the most.

V. Prototype

The aim of this prototype is to test all chosen visualization techniques and to provide a data explorer based on X3DOM and Data-Driven Documents. The resulting web-based application is shown in Figure 5.

A. Architecture

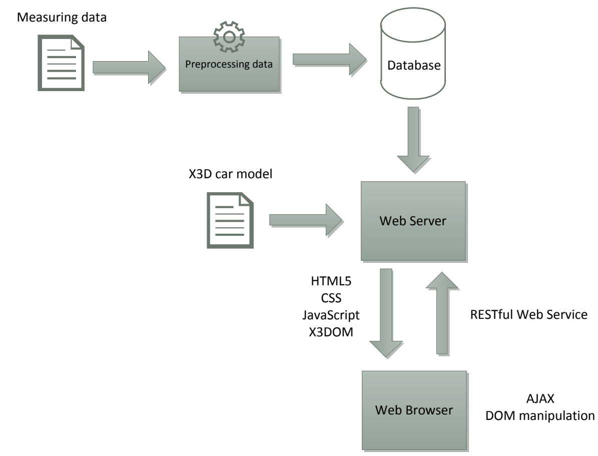

Figure 4. General architecture of prototypal implementation. Original and reduced approximated values are stored in database. Web server provides HTML content and data to the client. Client performs complete visualization using X3DOM and Data-Driven Documents.

The main parts of the prototype (see Figure 4) are a database, a web server and a client (a web browser supporting 3D within web sites). The major part of the applications logic is run within the client's web browser to provide dynamic visualizations, which respond quickly to user interactions. The web browser requests needed measuring data from the web server via RESTful web services and maps it into a data format that can be visualized by X3DOM or D^3. Hence, the web server primary has to provide the requested data and further visualization-specific calculations are performed client-side.

B. Data Preprocessing

Transferring all data to the client would be very time-consuming. Thus, the data is preprocessed to reduce network traffic. Generally, a measurement with n measuring points and t value acquisitions results to a data complexity of $O(n{\cdot}t)$. As the amount of measuring data can be massive, the Douglas-Peucker algorithm is used to to reduce the number of values [18]. This algorithm has an expected complexity of $\Theta(nt \cdot \log(nt))$; worst case is $O(n^2t^2)$. After applying this geometric algorithm, the reduced approximation of the original measurement curve will still preserve the overall structure. In other words, this algorithm filters all non-distinctive values. As users want to navigate through the data using different time-zoom levels, different degrees of approximations are needed, which are stored into the server's database after the preprocessing step.

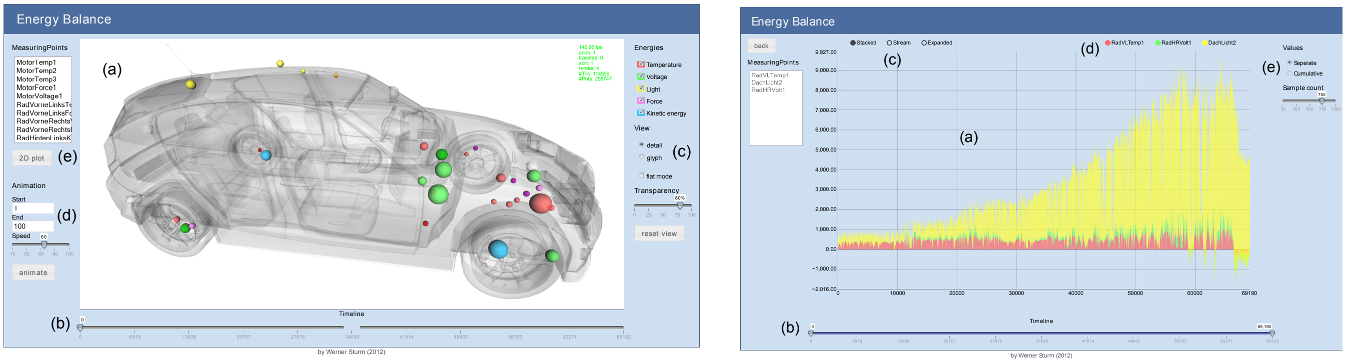

Figure 5. **left** Prototype displaying detailed data using Scaled Data-Driven Spheres. Real time 3D window provided by X3DOM (a). Timeline to navigate through time (b). Possibility to switch between detailed mode (SDDS) and overview mode using Cumulative Glyphs (c). Animated glyphs within specified period for three-dimensional trend analysis (d). 2D plot of values measured by selected measuring points for detailed trend analysis (e). **right** 2D representation of the data using Stacked Area Graphs. Graph is created using Data-Driven Documents library. Plot area for displaying the graph (a). Timeline to select a period to plot (b). Option to switch between Stacked Area Graphs (selected), Streamgraph (very similar to ThemeRiver) and Stacked Cumulative Percentage Graph (c). Possibility to select if measuring point is included in current graph (d). Switch between *seperate* and *cumulative* mode (d).

C. *Web Server*

Basically, the web server provides HTML content including a static 3D car model (for orientation and navigation purposes) in X3D format, which can be understood by X3DOM. However, the servers main task is to provide measuring data to the client. For that, it offers several RESTful web services, which provide the data in *JavaScript Object Notation* (JSON). Of course, clients do not receive all data at once. For both 3D visualizations (SDDS and Cumulative Glyph) the client commonly requests only data of a single moment. But all time-oriented, two-dimensional visualizations and animations of SDDS and Cumulative Glyphs, used for depicting the trend over time, need a data set of the desired time span. If users select a long period, which would cause a huge amount of data to be transferred to the client, the web server selects and sends the best approximation of the data. This allows the client to request any time span without overloading.

D. *3D using X3DOM*

The observer architecture of X3DOM, which connects the web browsers DOM with the internal X3D runtime, allows to modify the 3D scene via the DOM itself. Moreover, X3D predefines simple objects like box, sphere, cone and cylinder. Therefore, a SDDS can be created easily by using a sphere object (see listing in Figure 6).

Cumulative Glyphs can be created analogously using cylinders arranged circularly as depicted in Figure 3(a), (b). To animate glyphs to depict the values change over time, X3DOM implements *TimeSensors*, *Interpolators* and *Routes* defined by the X3D standard. *TimeSensors* provide a timer to trigger steady events within a defined period. *PositionInterpolators* are connected to *TimeSensors* via *Routes*, which provide a 3D vector interpolated between two defined vectors depending on the timers progress. These output vectors are passed to the spheres attribute *scale* (which expects a 3D vector) resulting a smooth animation showing a growing or shrinking sphere. Colors of glyphs also have to be changed during an animation. For that, X3D offers *ColorInterpolators*, which works analogously. This concept also supports long lists of key frames and therefore, any animation can be defined.

```
<scene id="scene" pickMode="box">
...
  <transform id="sdds1" class="sdds"
      translation="0 0 0" scale="10 10 10">
    <shape id="sphere1">
      <sphere class="sphere"></sphere>
      <appearance>
        <material id="material1"
           transparency="0.2" diffusecolor="#FF6666">
        </material>
      </appearance>
    </shape>
  </transform>
...
</scene>
```

Figure 6. Listing with X3D tags defining a Scaled Data-Driven Sphere.

E. *2D using Data-Driven Documents*

An investigation of multiple graphing libraries revealed that D^3 performs very well even with bigger data sets. Moreover D^3 can handle non-equidistant data points, which is needed to depict approximated data (as discussed before) without interpolating them explicitly.

VI. CONCLUSION

This paper investigates two- and three-dimensional visualization techniques to be used to visualize consumed and emitted energies, which have been measured within a vehicle, to support automotive engineers. In addition to that, a web-based prototypal implementation of chosen visualization techniques based on Data-Driven Documents for 2D and X3DOM to perform real-time 3D client-side is introduced.

Besides the measured value and its type of energy, the multivariate data includes spatial and temporal components. It revealed that Scaled Data-Driven Spheres are most suitable for a detailed 3D visualization of energy. This contributes to this research field that SDDS are also suitable for other scientific visualizations than medical visualizations. In addition to that, Cumulative Glyphs are presented to provide a better overview of the detailed data.

Both 3D-based techniques only visualize a single moment of the measurement period at once. Despite animations can represent the change over time, engineers want to analyze the trend in a more convenient way. Therefore, two-dimensional visualizations for time-oriented data are investigated in detail. Depending on the engineers requirement, Theme Rivers, Stacked Area Graphs and Stacked Cumulative Percentage Graphs support engineers to get a better understanding of the trend.

A successful implementation of a prototype shows, that all techniques can be implemented as a web-enabled application without the need of installing third-party browser plugins. It revealed some issues with X3DOM like web browser incompatibilities, but most of them exist because X3DOM does not implement all specified functionalities defined by X3D standard. Despite that fact, web developers benefit from both X3DOM and Data-Driven Documents, which enables them to implement interactive visualization applications without the need to struggle with low-level graphics operations like OpenGL or drawing single lines for 2D graphs. This certainly leads to lower development costs as well.

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