A Multi Level Time Model for Interactive Multiple Dataset Visualization: The Dataset Sequencer

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Abstract. Integrative simulation methods are used in engineering sciences today for the modeling of complex phenomena that cannot be simulated or modeled using a single tool. For the analysis of result data appropriate multi dataset visualization tools are needed. The inherently strong relations between the single datasets that typically describe different aspects of a simulated process (e.g. phenomena taking place at different scales) demand for special interaction metaphors, allowing for an intuitive exploration of the simulated process. This work focuses on the temporal aspects of data exploration. A multi level time model and an appropriate interaction metaphor (the Dataset Sequencer) for the interactive arrangement of datasets in the time domain of the analysis space is described. It is usable for heterogeneous display systems ranging from standard desktop systems to immersive multi-display VR devices.

1 Introduction

Simulations have become a common tool in many fields of engineering today. An integral part of computational simulations is a subsequent analysis process in order to verify the underlying simulation model or to make decisions based on the results of an efficient simulation. While complex phenomena in engineering sciences can seldom be described using a single model, different aspects are examined separately. In practice this was done with rather low coherence between the single simulation models in the past, omitting a lot of potential and accuracy caused by weak or neglected linkage between the simulation models. With the advent of integrative simulation approaches that connect simulation models at the data level to create contiguous representations of the simulated processes, the need for appropriate analysis tools arises.

A visualization of multiple datasets is often used to compare datasets to one another. Even more important this approach becomes for the exploration of complex phenomena that are not identifiable until multiple datasets are analyzed in a coherent view. For a multiple dataset visualization this demands for additional functionality in terms of interactivity as compared to traditional single dataset scenarios. The multiplicity of a multiple dataset visualization can be categorized into a horizontal and a vertical aspect [1], whereby the horizontal one addresses a temporal sequence of datasets and the vertical addresses different datasets describing the same time interval in different aspects (e.g. scales of scope). This work focuses on the interactive manipulation of the position of datasets on the horizontal axis as a means to explore the contiguous simulation results.

The remainder of this paper is organized as follows. Section 2 shortly explains the simulation platform developed to model and execute integrative simulations. Aspects regarding multi dataset visualization in contrast to single dataset visualizations are discussed in 3. Section 4 outlines the idea of a multi level time model and refers to appropriate related work. The interaction section (5) introduces the *Dataset Sequencer* interaction metaphor built on top of the aforementioned model. Finally section 6 concludes the work.

2 Integrative Simulation

In the domain of Materials Engineering, the idea of Integrated Computational Materials Processing (ICME) has evolved. It approaches the integration and interconnection of different material models [2, 3]. Different aspects of material evolution throughout a production process are simulated at different scales. A simulation platform has been developed [4–6] that enables collaborative simulation, utilizing interconnected simulation models and hardware resources, based on a grid-like infrastructure [7]. A key aspect for the coupling of simulation models is the correct translation of data between the single simulation models. For this, a data integration component has been developed that uses domain ontologies to assure semantic correct data integration [8]. Access to the simulation platform is given through a web-interface that allows for collaborative visual design of simulation workflows [4]. Beyond the integrated simulation itself, the analysis of integrated simulation results is an important aspect in order to gain knowledge and insight from those simulation efforts at all. The project concept of the simulation platform thus explicitly includes the aspect of visual data analysis.

For the analysis of the integrated processes, the visualization application has to deal with the multiplicity of datasets. Especially with the additional degrees of freedom in the interaction handling induced by it. In a pre-processing step each of the datasets is manually prepared and visualization primitives are extracted, i.e. the object's surface geometry or e.g. boundary edges of microstructural grains. In many cases domain specific knowledge is required in order to extract meaningful visualization primitives and thus this step cannot be automated completely yet. However, with the further development of the ontology based knowledge representation of the data integrator, some extraction cases could be automated in the future.

3 Multiple Dataset Visualization

The main characteristic that differs a multiple-dataset- compared to a single-dataset-analysis apparently is the common visualization context that needs to be established. At the technical level this imposes requirements for data management and interaction components that address this multiplicity.

Single datasets often exceed the available resources of a visualization system already. Even more does the integration of multiple datasets into a common visualization context. Thus, the incorporation of decimation techniques is mandatory. We have used different remeshing [9] and coarsening [10] approaches for this to prepare multiple resolution levels of the visualization primitives. Different detail levels can be selected at the beginning of a visualization session, e.g. to adapt to the current system's resources. Future work will focus on dynamic selection strategies that automatically adapt temporal and geometrical detail levels to the analysis context (cf. 6) at runtime. A fundamental component for dealing with multiple datasets is a data structure that provides structural, topological and logical meta information at different levels of abstraction. On the lowest level the relations between files on disk and how they buildup the single datasets (spatial and temporal) has to be modeled. Especially the interaction components in the system have to account for the multiplicity of entities at runtime and thus more information is needed about the relations the datasets have in the visualization context (spatial, temporal and logical) between the multiple datasets. Some modules of the runtime system need even more, specific meta information like e.g. the connection between different color transfer functions (lookup tables) and the datasets referring to it. Based on the concept of role-objects [11], the presented application provides a central data model to all of the different software modules the application consists of but at the same time maintains basic software engineering principles like high cohesion and loose coupling [12]. Each module is able to augment it's view on the data structure with specific data without interfering with other modules or creating inter-dependencies as it would be the case with a naïve shared data structure implementation.

Most existing multi dataset visualizations use a multi-view approach, consisting of side-by-side contexts, arranged in a grid on the screen, with each cell containing a single dataset, e.g. [1, 13, 14]. Generic visualization tools like ParaView [15] or EnSight [16] contain some functionality to work with multiple datasets in multiple views or even to merge a little number of datasets into one. Those are useful for a side-by-side comparison of two datasets, e.g. real data and simulation data (EnSight's "Cases" feature) or for the analysis of partitioned datasets. But those solutions do not contain features that assist in an interactive analysis of multiple contiguous but heterogeneous datasets that comprise a relation in the time domain. In contrast to these "multi-context" approaches, the presented solution uses a single context, which in turn can be extended to span multiple windows or displays. This makes it usable in multi-screen, and most prominently in immersive display systems, where the usage of multiple side-by-side contexts would disrupt the effect of immersion (cf. 5.1).

4 Multi Level Time Model

Time-variant data, which is the dominant kind of simulation results today, inherently contains a notion of time. When dealing with a single dataset in a visualization environment, the handling of spatial and temporal frames is conceptually not that critical. In practice both, spatial and temporal dimensions, are scaled to give a decent insight into the data, which could be interpreted as a normalization of the data presentation into the spatial and temporal attention span of the user and the display system he is using.

For a visualization of multiple datasets that have strong inter-relations, the spatial and temporal placement and the interactive manipulation of it have to be considered with much more attention. Although the spatial component in visualization and interaction is important, too, this work is focused on the temporal aspects. In the author's opinion, this aspect needs to be taken more into account for the complex visualization scenarios that are becoming more important today and probably will even more in the future. An example for this is the aforementioned domain of ICME that inherently needs to handle simulation data from different sources with heterogeneous temporal and spatial resolutions, modeling different aspects of material behavior during a production process [3]. Other domains of simulation sciences are most likely facing the same problems with the growing number of integrative simulation approaches.

Handling the temporal relations between datasets in an interactive environment introduces an additional degree of freedom to the analysis space: while all time instants of a single time-varying dataset can be reached with a linear navigation on the time axis, this is not enough for the multiple dataset case. To provide a flexible analysis environment, the temporal relations between the datasets inside the analysis environment have to be handled dynamically. This means that beyond the time-navigation itself, the manipulation of the single datasets' placement on the timeline has to be considered as well, to allow for the interactive comparative analysis of temporally related datasets.

4.1 Related Work

The idea of a temporal hierarchy is known and used in the fields of 3D Animation and Motion Graphics. Also work in the field of real time graphics, like the X3D standard [17] includes definitions of node types and so called *event routes* that could be utilized to process time information and thus to integrate a time hierarchy. But in the field of scientific visualization the notion of time is mostly limited to the mapping of discrete timesteps to a single linear time axis. Navigation metaphors stick to VCR-like controls, allowing only for linear navigation [18] and not for further interaction with the time domain. Though, for single-dataset visualization, this apparently is sufficient.

For exploratory analysis of multiple time-varying datasets the notion of a temporal hierarchy becomes important. Aoyama et al. [1] have proposed an application named *TimeLine* which includes – as the name suggests – a timeline view containing thumbnails for multiple data sources the visualization is using currently. But there is no interaction happening with neither the timeline visualization nor regarding temporal relations between the single data sources in general. The work from Khanduja [13] concentrates on Multi Dataset Visualization, focusing on interactive comparison of volume data, and addresses several aspects arising from this in comparison to single-dataset visualization. Temporal data coherence between timesteps in different datasets is exploited to reduce the runtime data load, but neither the temporal relation between the datasets nor any interaction in the time domain is taking place in his work. Wolter et al. [19] have proposed an abstract time model that describes the mapping between discrete time steps of simulation data and continuous time values, representing different aspects of time: *discrete time steps* represent a single time instant of the simulation. The *simulation time* refers to the time that a timestep represents in the original simulation's time frame. The *visualization time* normalizes the duration of the dataset into the interval [0..1]. The *user time* relates to the real-world time a user is acting in while viewing and navigating through an interactive visualization. While this time model fits very well for the handling of arbitrarily sampled datasets, this view is too granular from the viewpoint of handing multiple dataset in a dynamic fashion. The relation between multiple datasets is described in the continuous time domain and does not directly refer to the discretization of timesteps in each single dataset. A simple example clarifies the problem: If a dataset is moved on the time axis beyond the current boundaries of the overall visualization time, the normalized mappings of time values to all of the discrete timesteps of the overall simulation would have to be recalculated. The relative position of all discrete timesteps in relation to the overall timespan of the analysis context changes in that moment. For the static arrangement of multiple datasets this model is suitable, however for dynamic behaviour at runtime, additional work is needed.

4.2 Multi Level Approach and Runtime Time Model

The proposed solution for enabling a dynamic handling of temporal relations consists in building a hierarchy of multiple local time models as they were proposed by Wolter et al. [19]. Each single dataset's internal discretization issues are encapsulated by this very well, allowing to control each one by the normalized *visualization time*. The temporal relation between the datasets (i.e. their local time models) and the global timeline in which those are embedded can then be modeled as a graph, describing how the incoming global time needs to be transformed in order to make each dataset aware of its current normalized visualization time. Transformations that are needed to place each dataset in the temporal hierarchy can be reduced to *offset* and *scale*.

The meta information model includes an hierarchical representation of the data. From this, a directed acyclic graph of time-transformation nodes is built (cf. figure 1). During the update traversal of the application's event loop, this graph is propagated with the application timestamp which is then transformed through three levels (sequence, track, dataset, cf. 5) before the local time-models are reached. At this point the time value has transformed into the local normalized relative *visualization time*. The mapping of normalized time intervals to the discrete timesteps of the datasets is handled by each dataset's local time model ([19]).

An index structure is pre-computed that maps *visualization time* intervals to the appropriate timesteps. Finding the current timestep, i.e. the interval that contains the incoming time value, thus is realized by a lower bound query to that index structure. Sequential access is further accelerated by caching the last query result as the starting point for the subsequent query. Hence the additional runtime overhead caused by the multi level approach is negligible compared to a fixed arrangement of multiple datasets in the global temporal context. The graph needed to achieve the dynamic arrangement of datasets at runtime is very small as it only involves the datasets as a whole, not each single timestep.

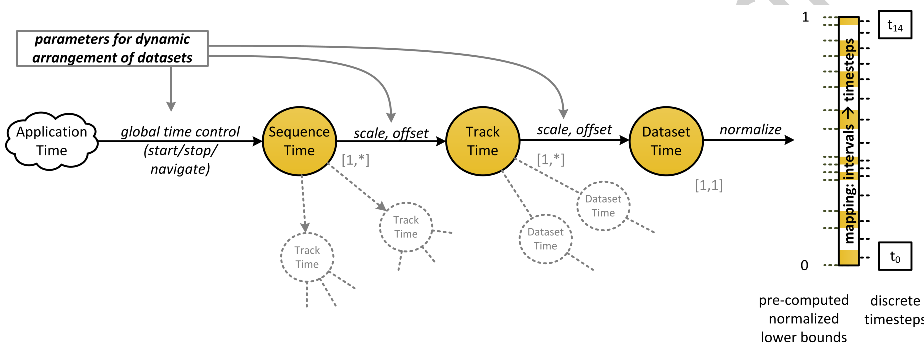
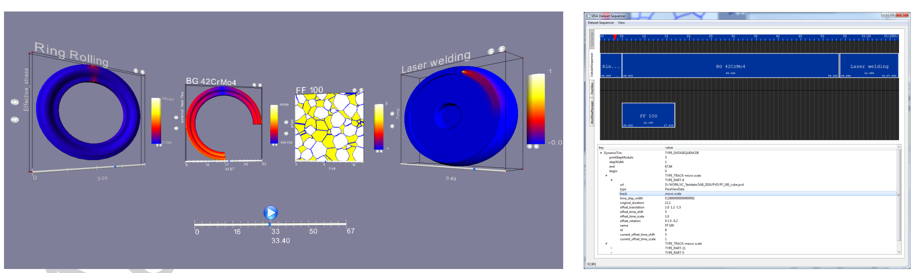


Fig. 1: Multi-Level Time Model: The application timestamp is dynamically transformed into the local normalized *visualization time* which then is mapped to the appropriate timestep using a pre-computed index structure.

5 Interaction - The Dataset Sequencer

The basic idea of an integrated process visualization is to provide the user with an environment for the analysis of the relations between the different process steps. Compared to the large number of work that can be found for interaction in the spatial domain, less approaches are known for the definition of temporal relations and appropriate interaction methods and no methodology for this has been widely adopted yet in the field of data visualization. While interaction metaphors for the spatial domain can be derived from real-world behavior, e.g. drag-and-drop interaction, an appropriately intuitive real-world paradigm is not available for the manipulation of temporal relations. Thus, for interaction in the time domain, more abstract interaction metaphors have to be developed. The interaction tasks for the integrative multi dataset visualization can be separated into navigation and manipulation, just like spatially characterized interaction tasks [20]. For the navigation, VCR-like controls are widely used (e.g. ParaView [15]) that allow for a linear navigation in the temporal dimension [18]. Interactive control over the inter-relations of the single datasets, i.e. the sub-aspects of the simulated higher-level process, in the time domain, can be categorized as a manipulation task: it changes the relation of the dataset to the global time axis and to other datasets in the visualization context. This allows to arrange for side-by-side comparisons of similar sub-processes (horizontal axis), e.g. material's behavior in a heating process, before and after a machining process that may change the material's behavior in the subsequent heating process. As multiple datasets at different scales may be involved, special care has to be taken to the temporal integrity of the displayed data. Datasets representing the same time intervals have to be consistently aligned in the time domain (interlock on the vertical axis). If this constraint is violated, an inconsistent and simply wrong visualization state occurs that could induce an incorrect mental map [21] of the visualized data to the user, invalidating the whole analysis process in the worst case.

In the field of audio and video production, clip-based editing and organization of audio/video events on multiple parallel timelines is a common approach, e.g. with digital audio workstations like *Cubase*[1] these concepts have matured since the late 1980ies. Our approach tries to utilize akin interaction and 2D visualization methods for the interactive placement of datasets on multiple tracks embedded into a global timeline. The idea of using such an interaction metaphor as a means for real time interaction with a multi-dataset visualization is - to the best of our knowledge - a new approach.



(a) (b)

Fig. 2: (a) 3D Visualiaztion (b) 2D User-Interface of the Dataset Sequencer.

Figure 2 shows an integrated visualization scene and a first prototype of the presented Dataset Sequencer 2D interface. On a global horizontal timeline the datasets are represented as rectangles extending the time interval they are active in. Multiple *tracks* are stacked vertically to place concurrent datasets, e.g. representing micro- and macro-structural simulations. The temporal position of

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a datasets in the overall context thus can be intuitively depicted an manipulated by drag-and-drop interaction. Additional hints, like the original alignment of datasets, help the user to keep track of the original context. Additional meta information about the datasets can be queried and manipulated inside the 2D interface (lower part). This allows for exact setting of e.g. the *scale* and *offset* values or direct entry of begin/duration values for a dataset. The initial configuration and the logical relations and grouping information is stored in the aforementioned meta data structure. Explicit begin time values as well as scale-factors and offset values (temporal as well as spatial) can be used for the description of the initial setting. Another option allows for an automatic alignment for the initial setup that simply queues each new dataset to the end of the track it has been selected for.

5.1 Hybrid 2D/3D Interaction

The presented visualization application is targeted to drive heterogeneous display types, e.g. using head-tracked stereo rendering and immersive input devices as well as standard desktop workstations or notebooks. For the navigation tasks VCR-like time-slider controls are embedded into the 3D visualization context (cf. figure 2). Each dataset has a time-slider attached that scrolls through it's timesteps. The thereby selected timestep is displayed as long as the slider is grabbed or when the global time control is paused. An additional free-floating time-slider controls the global time. This approach works well for navigation tasks in the time domain. Approaches to use the sliders for the manipulation of the temporal relations turned out to be useless as no valuable feedback could be provided to represent the influence of the interactive manipulation to the global relations instantly. Additional graphical objects in the scene could be used for this, but as the multiple datasets already occupy the visualization space and additional objects just would clutter up the scene, this approach was not further pursued. Thus this task was split off into the more abstract 2D Dataset Sequencer GUI.

The target display systems for the multiple dataset visualization application are heterogeneous, thus the 2D interface and the core application communicate over a network interface, utilizing the aforementioned (cf. section 3) meta data structure. Depending on the target display system, the Dataset Sequencer GUI can be used in a windowed application side-by-side to the 3D Context on a desktop machine, or on a separate, “control panel” like machine, e.g. in front of a power wall, or on a tablet device literally inside a fully immersive CAVE-like environment.

6 Conclusion & Future Work

We have presented interaction methods for the handling of multi dataset visualizations. Focusing on the temporal aspect of an integrative visualization context, a multi level time model has been presented. A hybrid interaction metaphor for the navigation and manipulation in the temporal dimension suitable for heterogeneous display system architectures has been developed that utilizes 2D and 3D interaction metaphors. The 2D interaction metaphors are based on non-linear editing concepts found in media production industry but utilizing this concept for interaction with a real time visualization application depicts a new approach in the field of data visualization. The aim of the Dataset Sequencer UI however is not to resemble all the high-sophisticated editing capabilities of audio or video production systems, but to develop interaction methods that ease and assist the analysis process in a multiple dataset visualization environment, inspired by these editing techniques.

The main focus of future work will concentrate on the data handling problem residing in the handling of multiple datasets. Considering the temporal and geometrical resolution of the involved datasets as well as data-driven importance metrics and available system resources, heuristic detail selection methods will be researched. Those will provide context sensitive behavior of a dynamic detail selection framework. Other aspects include the refinement of the 2D user interface, for example automatic alignment and vertical interlocking of datasets in the timeline will be improved. The incorporation of data plots into the sequencer view will provide the analyst with more guiding information allowing for easier orientation in the integrated environment of the datasets. In the other direction, user-drawn graphs, sketched within the 2D interface, could be used as an importance metric for the detail selection methods.

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