Bidirectional Coupling Between 3-D Field Simulation and Immersive Visualization Systems

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The interactive exploration of complex simulation data have spurred a renewed interest in visualization techniques, because of their ability to give an intuitively clue for the interpretation of electromagnetic phenomena. This paper presents a methodology for a bidirectional coupling of VTK-based visualization systems to interactive and immersive visualization systems which are specially adopted for the handing and processing of large and transient simulation data. In this work, the coupling is demonstrated by the flexible virtual reality (VR) software framework ViSTA which is used by many national and international research groups.

***Index Terms*—Electromagnetic data visualization, interactive computing, interactive postprocessing, scientific visualization, virtual reality.**

I. Introduction

TOGETHER with the development of computers, simulation software has attained nowadays a rather high level of sophistication. In many real-life engineering situations, the problem is no longer to be able to simulate, but rather to be able to interpret correctly and efficiently the huge amount of numerical information generated by the simulation. Visualization has been regarded so far as an auxiliary task in finite element (FE) modeling that was limited to the servile representation of simulation results. But together with the increase in the complexity of simulation data, the interest in appropriate visualization systems is renewing nowadays. The general requirement for such systems is to enable a fast or even sub-real-time graphical representation of transient simulation data, irrespective of its data volume. For such a scenario, specially adapted software concepts are required to fulfill such criteria. This paper presents the idea and the technical background of a bidirectional coupling of the VTK-based electromagnetic visualization tool Trinity.IVR and the VR-framework ViSTA.

II. Related Work

In many research projects the coupling of different software frameworks and software tools are an important issue. In [1] Schopfer *et al.* present an integration platform (CHEOPS) for the modeling and simulation of chemical processes. In this approach an overall integration framework is provided in which all simulation and visualization tools are integrated. Riedel *et al.* present a network-based coupling of the visualization tool VISIT and existing simulation algorithms running on a high-performance computing (HPC) system. Within the CONV project [2] the VISIT internal client-server architecture is used for handling the coupling process. In addition to these approaches for coupling different software tools there are also solutions for coupling algorithms to enhance the capabilities of an existing software framework. In [3] Raffinn *et al.* describe the coupling of algorithms for mass-spring systems and deformable objects with an existing VR Software framework to process distributed physical based simulations. Our approach builds upon the ideas of the presented papers and on our prior work presented in Section III.

III. Previous Work

In 2001 the Institute of Electrical Machines (IEM) developed the command line based software tool iMoose.trinity [4] which provided a liberty of visualization algorithms for the electromagnetic field problems. The commands were realized in Python [5], so that users could assemble static visualization scenes in an individual Python script. Within the scope of [6] its enhancement iMoose.trinity.VR [7], [8] has been developed, which applied the Open-Source Visualization Tool KIT (VTK) [9]. In 2009 the IEM started the development of iMoose.trinity.IVR [10] and new electromagnetic visualization methods [11], [12]. This software tool combines the advantages of both former packages and is integrated in the day-to-day visualization of FE data. Its concept is designed to add FE postprocessing and processing facilities as long term research goals.

Beside the development of VR capabilities focusing on electromagnetics, the VR toolkit ViSTA [13] and the extension for flow phenomena ViSTA Flowlib [14] have been developed in the course of many research projects. ViSTA is a flexible and extensible software framework which is already productively used by many national and international research groups [15]. ViSTA has a scalable interface that allows its deployment in desktop workstations, small and large VR systems, like the 3-D workplaces or CAVE-like systems. Hence, new modules and concepts are easily integrated and can be used on a wide range of different systems. Another important feature of ViSTA is its focus on advanced interaction techniques for full and semi-immersive environments like Cave or 3-D workplaces.

IV. Goals and Methodology

The main goal of this work is to provide a framework for a flexible coupling between ViSTA and iMOOSE-Trinity, which is not regulated by the restrictions of certain middleware software, e.g., CORBA [16]. The coupling methodology presented here is only focusing on the VTK layer for realizing the coupling strategy, which generally allows an interconnection to any VTK-based visualization environment. Regarding the fact that ViSTA and iMOOSE-Trinity are both using VTK pipelines, new functionality can easily be integrated in both software tools during the coupling process.

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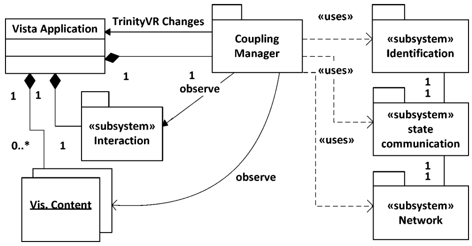


Fig. 1. Collaboration between the ViSTA application and the coupling extension.

A direct integration of ViSTA into iMOOSE-Trinity is not suitable because both pieces of software have their own data structure and different purposes. Both systems are expert systems with their own internal logic. The coupling must not be regarded as a mere integration, but rather as an enhancement of functionality. The purpose of this coupling is to offer the possibility to link a simulation package with the whole range of immersive visualization systems, from 3-D office systems up to cave-like systems.

The outstanding idea which is in the focus of this work, is to implement such a linkage between software packages by a generalized network-based bidirectional coupling. Since techniques like making interactive cuts or seeding particles for flow (or flux line) representation are common in both systems such a mechanism mirrors all performed actions from one system to the other, so that one ends up with a consistent representation on both environments. This mirroring leads to an observation of all responsible state changes on each system, which are directly transfered to its counterpart.

The benefit in such an additional effort is to provide an extended electromagnetic processing and post-processing framework, where users employ the advantages of immersive VR-Systems, e.g., the interactive point or surface selection in 3-D by switching from the standard GUI-based finite-element environment directly to such professional VR environments.

For instance, in the case of leakage flux visualization, the interaction for navigating to the points of interest takes place in the ViSTA driven application feeding the iMOOSE.Trinity algorithm, which computes the corresponding closed magnetic flux lines. Since these algorithms provide VTK visualization data which are directly associated with graphical primitives, the coupling mechanism supplies these data objects on other display systems. These type of interactions entails back-and-forth communications between ViSTA and iMOOSE.Trinity to achieve a seamless coupling integration, which can be utilized in the classical finite element based design processes of electrical drives.

The allover design goal of mirroring functionality through different applications is far from being trivial and represents the major task of this project. This is even more true, when introducing vital side conditions, demanding minimal code changes in the FE simulation package to guarantee that further development features are compatible to the proposed coupling method. The technical background to do so is presented in Section V, starting from the high level software design concept towards its practical implementation.

V. Software Architecture

A. High Level Concept

The software architecture of the coupling is deduced from the requirements. The identified requirements are:

- a coupling mechanism which directly relies on the VTK-framework to enable a linkage to any VTK-based application;
- minimal code changes in the VTK-based application in order to achieve that no implementation overhead is generated for the further development of the application;
- accumulation of necessary code changes on a single point of contact.

Fig. 1 shows the high level concept of the ViSTA based coupling, showing a coupling manager (CM) as central element of the communication relay. On each side the CM communicates state changes and arbitrary procedure calls with its counterpart listening on the base application. This manager is instantiated in each application and represents a single point of contact, using the facade pattern [17], for code changes and application enhancement as listed in the requirements above. To fulfill the requirement of minimal code changes within the application certain subparts of the program like the interaction subsystem and visualization content (see Fig. 1) are exposed via observer pattern to the CM, allowing the CM to observe their state changes without having any interdependence between them. In this context the observer does not need to have any application-specific knowledge of the observed application. Moreover, the ViSTA-CM detects all changes incoming from the VTK application, also utilizing such a concept. Thereby, the CM encapsulates the complete coupling subsystems like network and state processing from the application itself, which are necessary to communicate internal changes with its counterpart (see Fig. 1).

To guarantee a further single usage of ViSTA and iMOOSE-Trinity the code changes are restricted to a minimum. In the coupled mode each application has to run a couplingmanager that encapsulates the layers in between and handles state changes generically. The applied facade pattern mentioned above is like a collection of all required interfaces in one class. In practice the couplingmanager provides a network interface to address the machine the coupled application is running on. Furthermore, the application registers itself and the parts that should be synchronized between the applications. Modifications to most parts of the applications are made in derived classes. To encapsulate the different class instantiations of the coupled mode and the normal one, all instantiations are handled by a class-factory [17]. In VTK these factories are already available and were only extended.

B. Concept of Remote Objects

This section will introduce the concept of logical objects called RemoteObjects like state data, the visualization content or remote-procedure-calls(RPCs) [18]. Since the application coupling is targeting the visualization and the user interaction, the low level coupling concentrates on exchanging the states of the visualization content and the user interaction. For example both applications handle and visualize VTK visualization pipelines. One visualization pipeline describes one piece of visualization content. But these visualization contents are used in different window systems due to the fact that ViSTA is an application for heterogeneous display systems. The fact that parts of the applications do the same (visualizing content) but partly work differently motivated the concept of RemoteObjects. These RemoteObjects shall describe a logically equivalent part of each application with different implementations. RemoteObjects will allow a tight coupling and a generic state update mechanism over network on a per-object level. In this case a

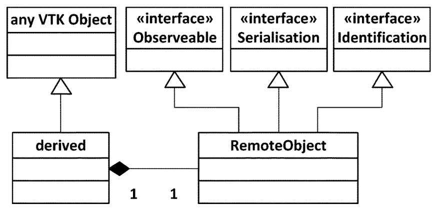


Fig. 2. RemoteObject class diagram.

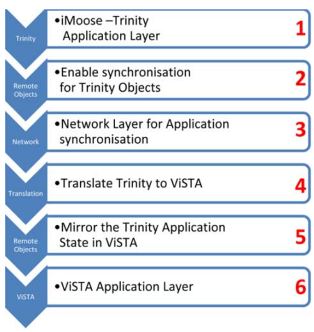


Fig. 3. State handling between iMOOSE-Trinity and ViSTA.

tight coupling stands for a communications interface between both applications to synchronize their states.

The concept for a generic handling of state updates requires minimal interface changes in the VTK application as shown in Fig. 2. To minimize the API changes for a VTK application, all coupling mechanisms are implemented in derived classes from standard VTK objects. Each derived class aggregates a more generic RemoteObject which encapsulates the state handling including the state update processes. To enable the communication of state changes in an appropriate granulation the Observer Pattern [17] is applied.

To minimize the network traffic of state updates, the existing VTK observer mechanism which is generally available on each VTK object, is extended to provide a finer granularity. Finer granularity means in this case a higher level of detail to allow the observer mechanism to react only on the specific state changes on each VTK object. This results in a minimal communication overhead for large visualization objects, which are characteristic for FE computations (e.g., vector solution data), since only incremental changes are considered. This concept completely differs from the standard VTK state changes communication which is part of its pipeline principle resending modified objects completely. The VTK pipe concept is explained in [9]. Secondly, each RemoteObject implements a serialization and deserialization interface to enable network communication (see Fig. 2). Thirdly, a mechanism for unique object identification was applied. These object IDs had to be synchronized in both applications. Derivation is used instead of any other software design pattern, in order to enhance the class functionalities; also derivation preserves their normal usage and interfaces. In order to mirror the white rendering window of VTK, one just has to derive this class together with the RemoteObject pattern described above. This modified VTK base class replaces the prior used rendering window, so that each executed setter function calls the trigger for its normal VTK behavior and additionally communicates these changes to the corresponding RemoteObjects. The latter applies a standardized state update in the CM, so that all information is transferred to the ViSTA application.

C. Datafow Description

The analogy of a layer-based software architecture can be used to explain the flow of information where both applications use a couplingmanager, each synchronizing arbitrary RemoteObjects over the network. The software layout of the coupling mechanism consists of six layers each, describing a specific task in the state handling process, see Fig. 3. The first and last layer represent the application layers of both participating programs. These programs were extended to communicate a generic object state update.

Each layer in between is part of the state transcription. The arrows associated with each layer represent the type of communication, whereas its communication direction between layer one and six can be reversed to ensure a bidirectional coupling interface. The synchronization of the iMOOSE-Trinity application and its runtime states on an per-object level is realized by RemoteObjects. RemoteObjects are automatically synced via Network.

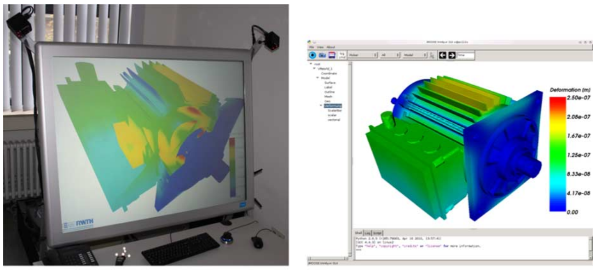
Layer three represents the network communication. It is optimized for bidirectional synchronization states and considers the problem of parallel state manipulation. In most cases communication is handled asynchronously using Asynchronous Completion Token [19]. Semaphore locking and synchronous communication is used to preserve data integrity in vital parts like the unique object identification. The network connection is capable of direct socket connection on a single machine and communication over TCP/IP.

Since both applications use VTK techniques underneath, the overhead to enable them to communicate is limited to the interaction and RPCs in the majority of cases. The translation of logically equivalent tasks between the ViSTA and iMOOSE-Trinity, e.g., a camera update by an input device is handled in the fourth layer. But it is far from being trivial to realize this translation, because application-specific knowledge from each side are needed to succeed in this task. The implementations follow the Adapter pattern. The exchange of the visualization content is achieved by the VTK-Legacy format hence no conversation between graphical data at runtime is required.

In layer five the translation not of objects but of the interaction of classes is managed e.g., ViSTA supports multiple display systems, camera updates are more complex than in VTK and handled in more than one class. In this layer a efficent selection of logical equivalent objects is essential for a clearly laid out software architecture. Furthermore the application of the RPCs is done.

VI. Application and Practical Issues

Even if professional immersive visualization systems are available today, such systems are seldom used as part of the design and development process of electrical drives to capture the influence of single, mostly local, phenomena with respect to design variations. The main reason for avoiding such techniques is rather simple and driven by practical issues. The finite element simulation data for an appropriate visualization needs to be exported as graphical primitives or interpolation fields, yielding a static scene. The latter can afterwards be explored by different graphical techniques relying on these basic primitives. Since these kinds of data structures are comparable small to all additional information data necessary for FE computations, one yields a visualization system which is able to show a fast or even sub-real-time representation of transient simulation data. A drawback is the loss of any possibility to apply specific processing or post-processing routines, requiring the specific field solution together with its underlying



(a) (b)

Fig. 4. Visualization of the transient deformation caused by electromagnetic forces using bidirectional coupling. (a) VR System running ViSTA, (b) Screenshot of Trinity.

element shape functions, which are exclusively hosted by the FE software package. Using the presented methodology for coupling both specific applications (FE-simulations package, ViSTA), all enhanced features available in immersive environments can be utilized as part of design and development processes for electrical machines.

The usage of the bidirectional coupling between Trinity and ViSTA is described in the following part, cf. Fig. 4. Fig. 4(a) shows a VR System of an electromagnetic dataset, e.g., a desktop-based VR System. This system is equipped with 3-D stereo technology and a infrared-based tracking system. The infrared cameras on the top of the screen capture a single user wearing 3-D glasses equipped with markers. The user's position is detected to adapt the scene in order to provide a user-centered projection, which allows a more intuitive view on the dataset. The same tracking system enables advanced interaction techniques which generally offers six degrees of freedom. For instance, one can employ this technique to provide an interactive exploration of complex geometries by defining clip planes in dependency of the distance between screen and user to enable an intuitive evaluation. By leaning towards the model such clips basing on the visualization data are performed. This situation is depicted in Fig. 4(a).

Fig. 4(b) shows a screenshot of Trinity showing the same dataset. With the usage of Trinity one still has the same set of functions for visualizations, which are handled and organized by the tree-oriented data representation (left part). The latter user interface is specialized for a 2-D based GUI. Since all visualization objects, e.g., for meshes, scalar and vectorial solutions, contain a VTK-based representation and are directly associated with the corresponding FE-data as described in [11], the post-processing operations are directly addressed to the current visualization (main window). These operations can either be steered graphically or by the command line (lower part). Moreover the usage of interaction methods for data-manipulation, which are adapted for the application without a steroscopic view, are also possible, see [10], [11].

Due to the data consistency, described in V, all further operations requiring finite element methods are still available, without facing the user with any kind of technical barrier, e.g., explicit data exchange, data conversion, etc. Therefore, this approach can help to integrate all beneficial enhanced VR features to FE packages as long term research goals.

VII. Conclusion

Efficient methods for the visualization of finite element solutions are essential for the evaluation of electromagnetic devices under research and development. This paper presents a generalized software architecture for the coupling of VTK-based graphical representations to use full and semi immersive visualization systems. The object state handling described in this paper allows a seamless interconnection between both systems without affecting and touching the other one. Since the presented work is currently in a prototype-phase it is strongly necessary to carry out significant user studies with scientists dealing with electromagnetic phenomena in the next steps. The results of these user studies and feedback from the scientists will be used in order to improve and enhance the provided coupling functionality.

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